Mono-X, Associate Production, and Dijet searches at the LHC

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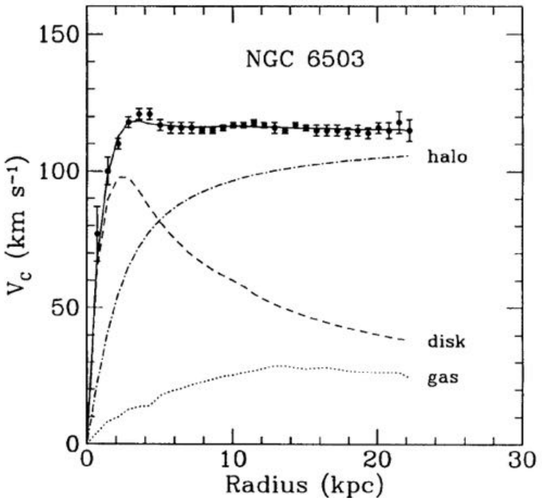
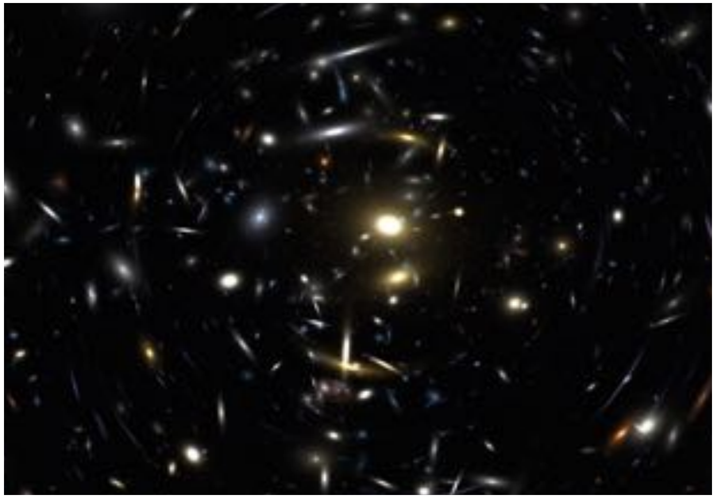
The University of Melbourne

CAASTRO-CoEPP Joint Workshop
Melbourne, Australia
Jan. 30 - Feb. 1 2017

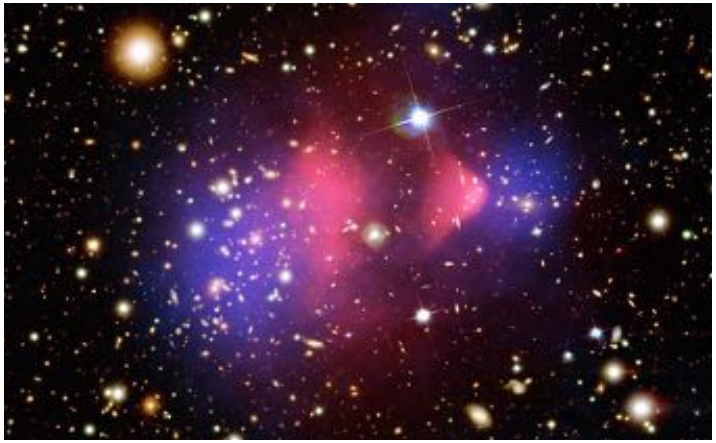
Observational Evidence of Dark Matter



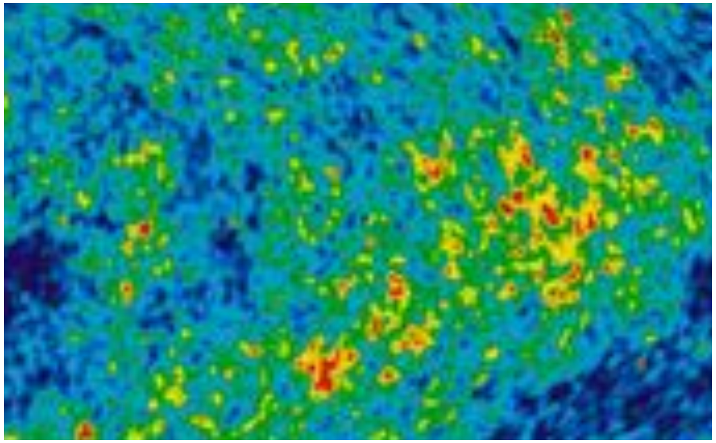
Galaxy rotation curves



Gravitational lensing



Cluster mergers



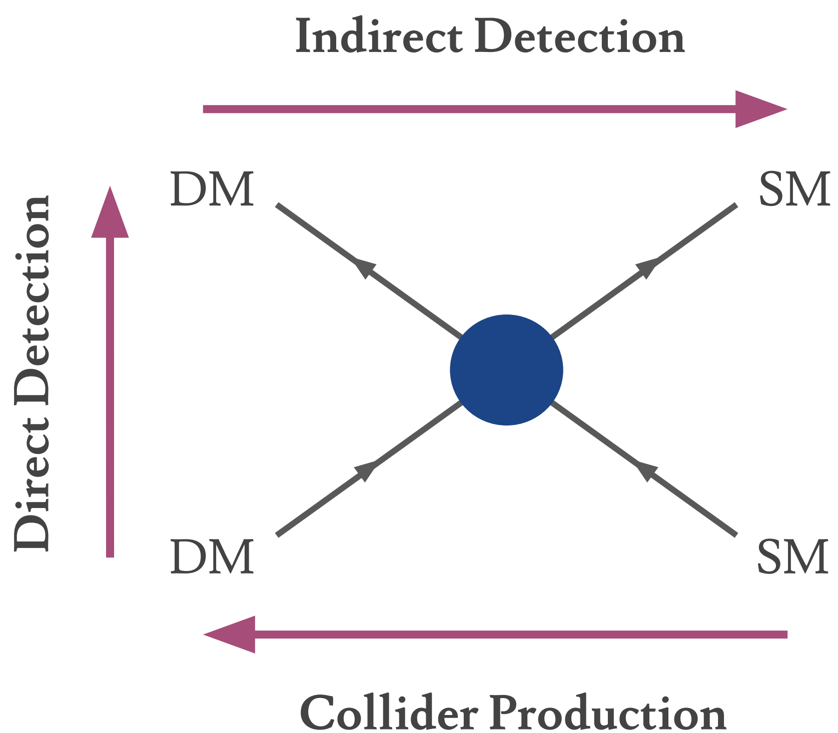
CMB

And much more!

Dark Matter Detection

Experimental evidence motivates a DM sector composed dominantly of Weakly Interacting Massive Particles (WIMPs)

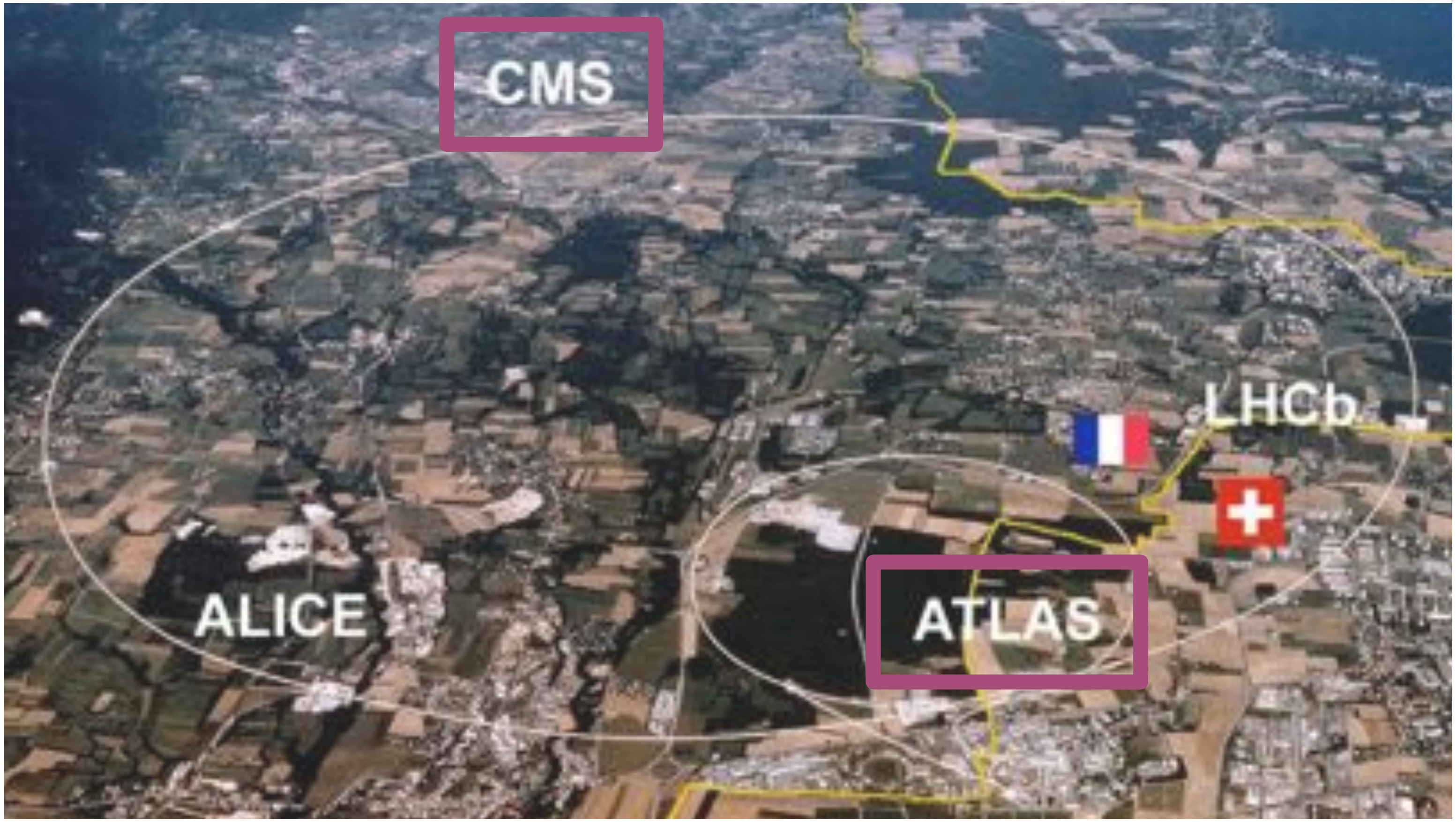
➔ Facilitate comparison of results in the three main DM detection avenues



The Large Hadron Collider (LHC)

A proton-proton and heavy ion collider in Geneva, Switzerland

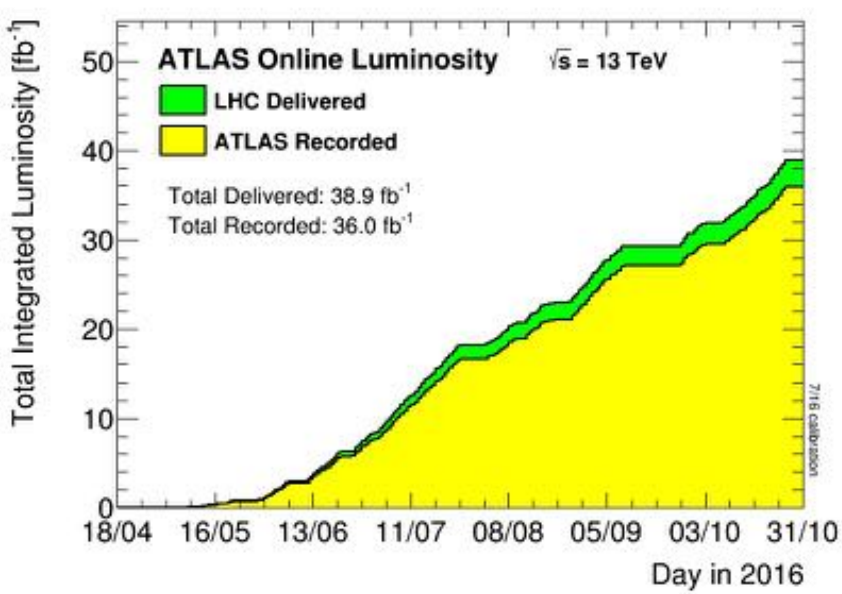
➔ Four collision points, two of which are housed within general-purpose detectors; **ATLAS** (A Toroidal LHC ApparatuS) and **CMS** (Compact Muon Solenoid)

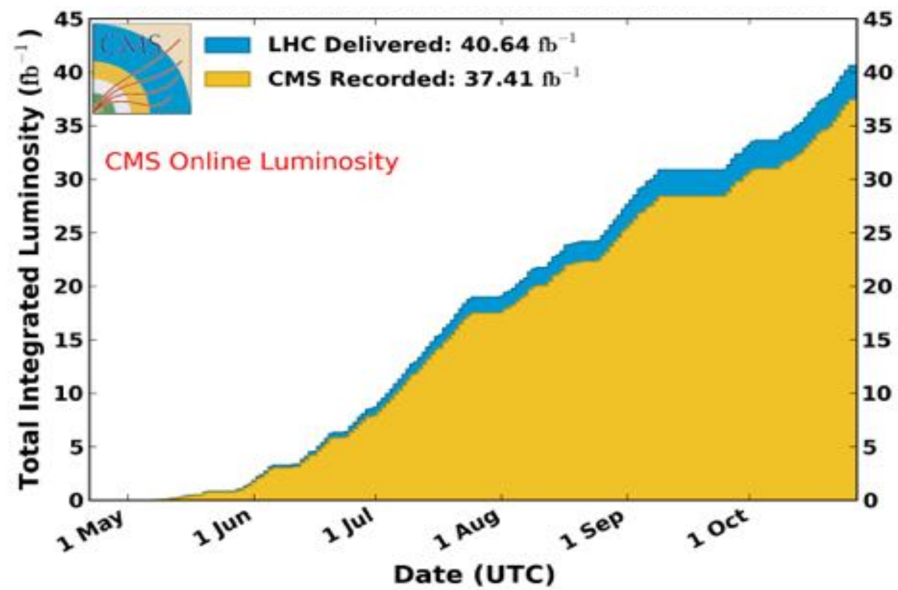


Dedicated proton-proton collision schedule

➔ From 2010 to 2012 (Run-I), collected ~25 fb^{-1} of data at a centre-of-mass energy ($\sqrt{s}$) of 7 and 8 TeV

➔ In 2015 and 2016, moved to $\sqrt{s}$ = 13 TeV (Run-II) → ~36 fb^{-1} (ATLAS) and ~37 fb^{-1} (CMS) of recorded data

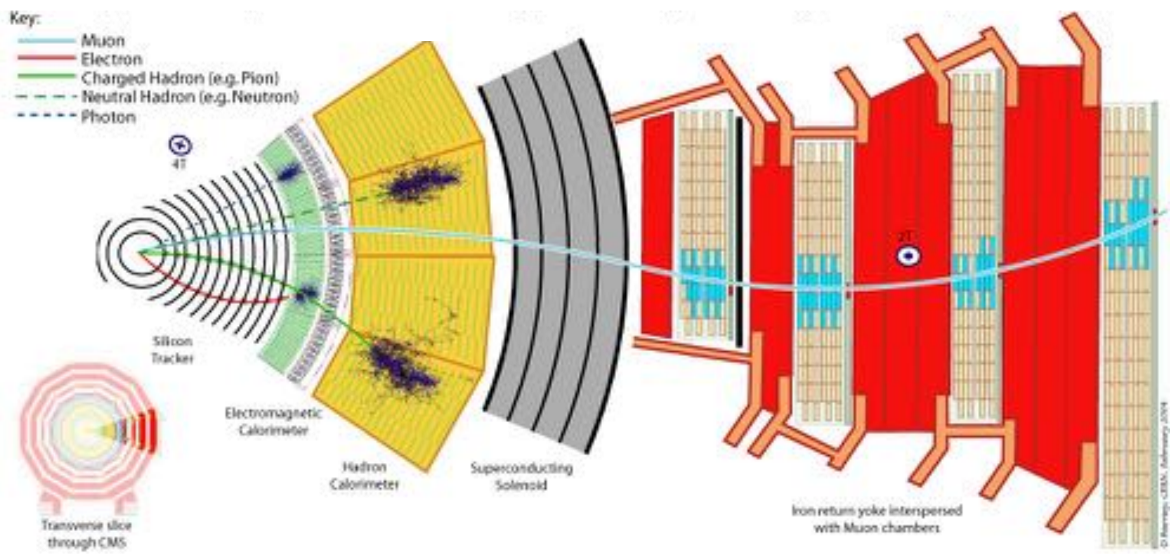




The ATLAS and CMS Experiments

ATLAS and CMS aim to detect a wide range of possible New Physics signals

- ➔ Particles reconstructed with information from detector sub-components
- ➔ Efficient identification of particle type, energy, and momentum



- ➔ Invisible particles escape detection but present as a momentum imbalance in the transverse plane; Missing Transverse Energy, $E_{\mathrm{T}}^{\mathrm{miss}}$

$$E_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathrm{miss}})^2 + (E_y^{\mathrm{miss}})^2}$$

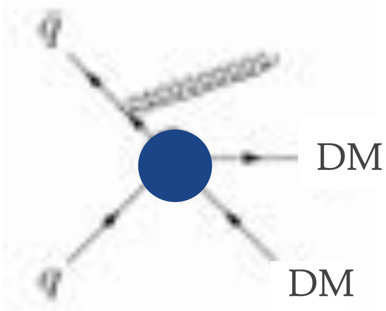
$$\phi^{\mathrm{miss}} = \arctan(E_x^{\mathrm{miss}}, E_y^{\mathrm{miss}})$$

Dark Matter Collider Detection Channels

Mono-X Signal

WIMP DM doesn't interact with detector
➔ Require a SM particle, X, in the FS

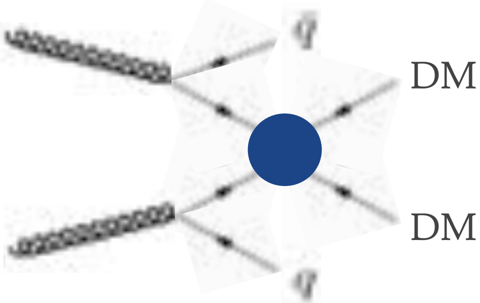
Search strategy: look for jet(s), W/Z/Higgs, or γ plus large E_T^{miss}



Associate Production Signal

Mediator with Yukawa couplings to SM/DM particles
➔ DM produced in association with heavy-flavor quarks

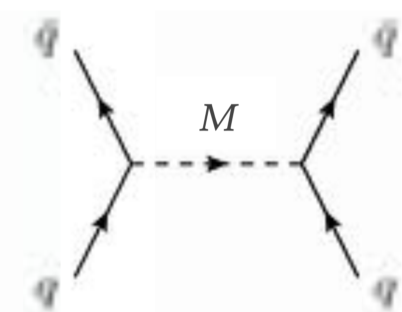
Search strategy: look for b/t quarks plus large E_T^{miss}



Di-jet Signal

DM produced via decay of a new heavy resonance
➔ SM coupling permits decay to light qq pair
➔ Decays to tt, WW, ZZ also permitted (di-X signal)

Search strategy: look for bumps in m_{jj} distribution



Theoretical interpretation of results

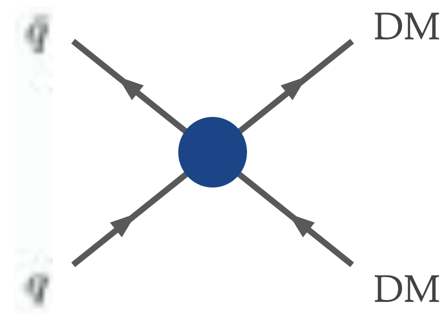
Run-I searches interpreted with **Effective Field Theories (EFTs)**

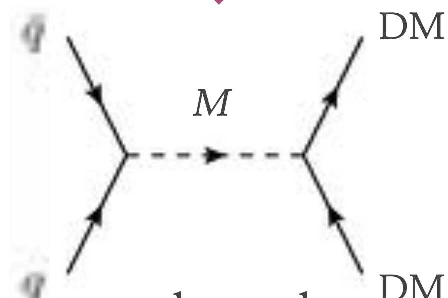
- ➔ Free parameters: m_{DM}, and $M_* = M/\sqrt{(g_q q_\chi)}$
- ➔ Valid when M >> Q
- ➔ Heavily restricted range of validity at the LHC

Run-II searches focus on **Simplified Models of DM (SiMs)**

- ➔ Five parameters: M, Γ, m_{DM}, g_q and q_χ
- ➔ Benchmark set of SiMs/parameters agreed upon at joint theory-experimental **LHC DM Forum**
- ➔ Results presented in a universal manner
- ➔ arXiv: 1507.00966, arXiv:1603.04156

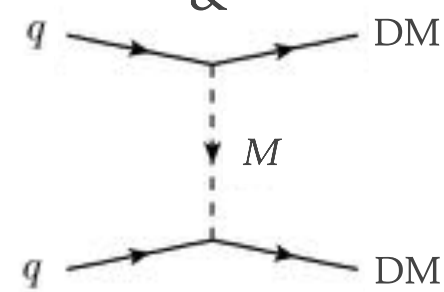
This talk will focus on SiM and EFT interpretations of the most recent Run II DM searches





s-channel

&

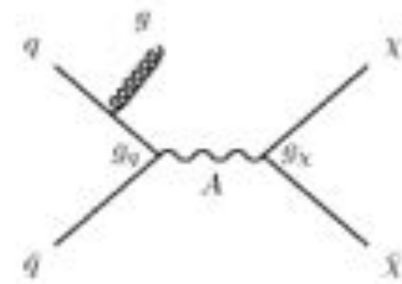


t-channel

Mono-X Searches

ATLAS Mono-Jet Analysis

Mono-jet channel most sensitive to DM production at the LHC



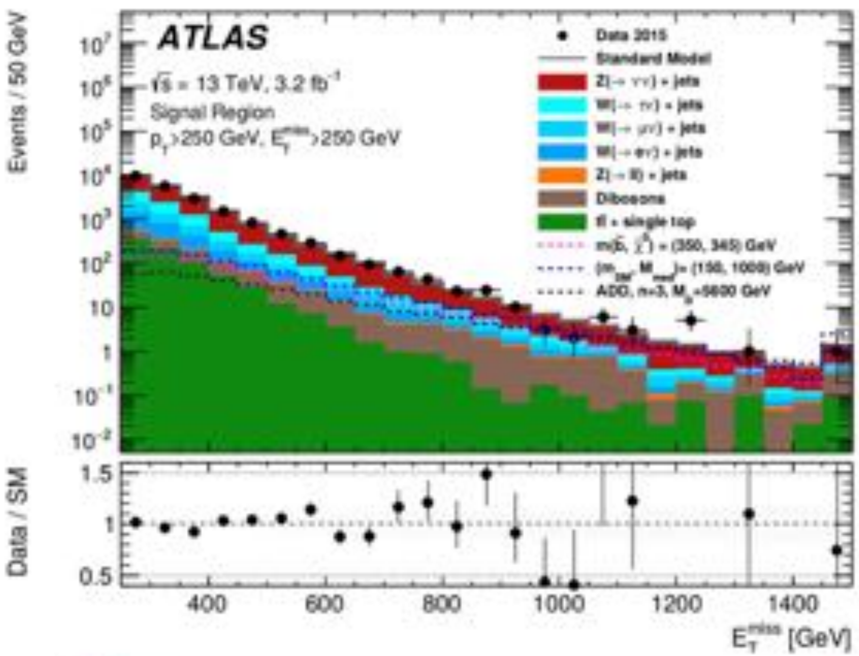
Selection: At least one high-p_T jet and large E_T^{miss}

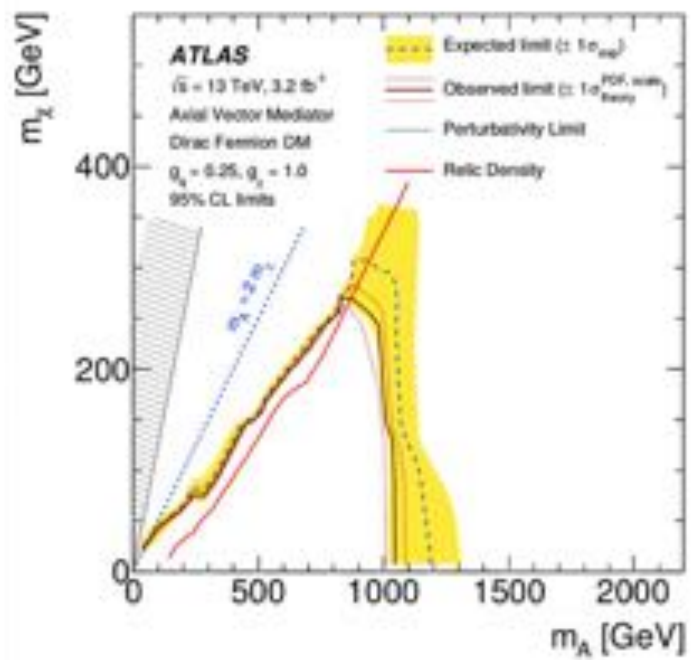
➔ Jet clustered with anti-k_T algorithm with R = 0.4

Dominant Background: $Z(\to \nu\nu)$ + jets

➔ contribution normalised in control regions for several E_T^{miss} bins, using a global fit

Model(s): Leptophobic Z' mediator with axial-vector couplings





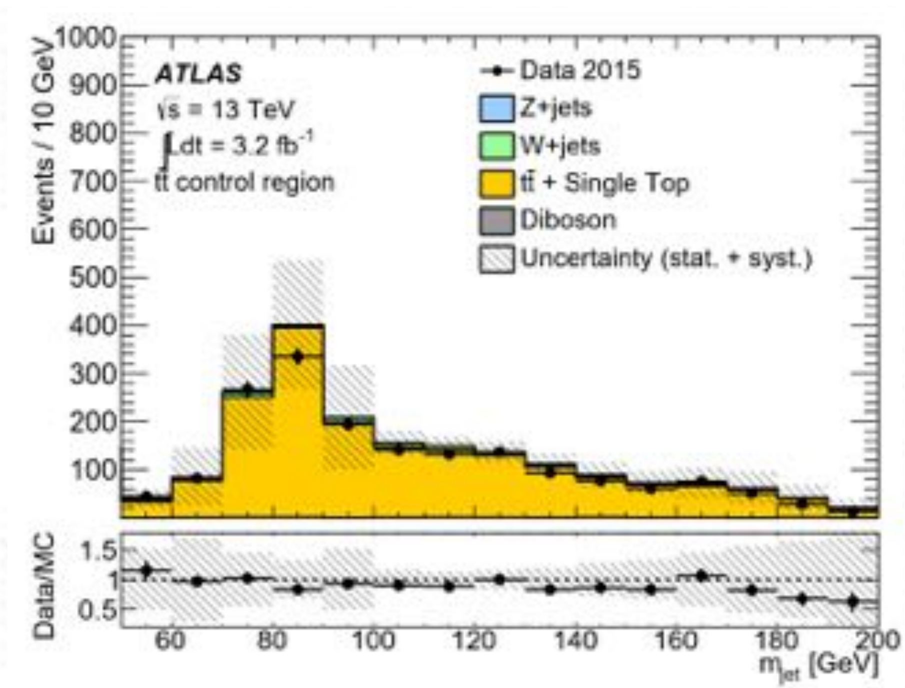
[Phys. Rev. D 94, 032005 (2016)]

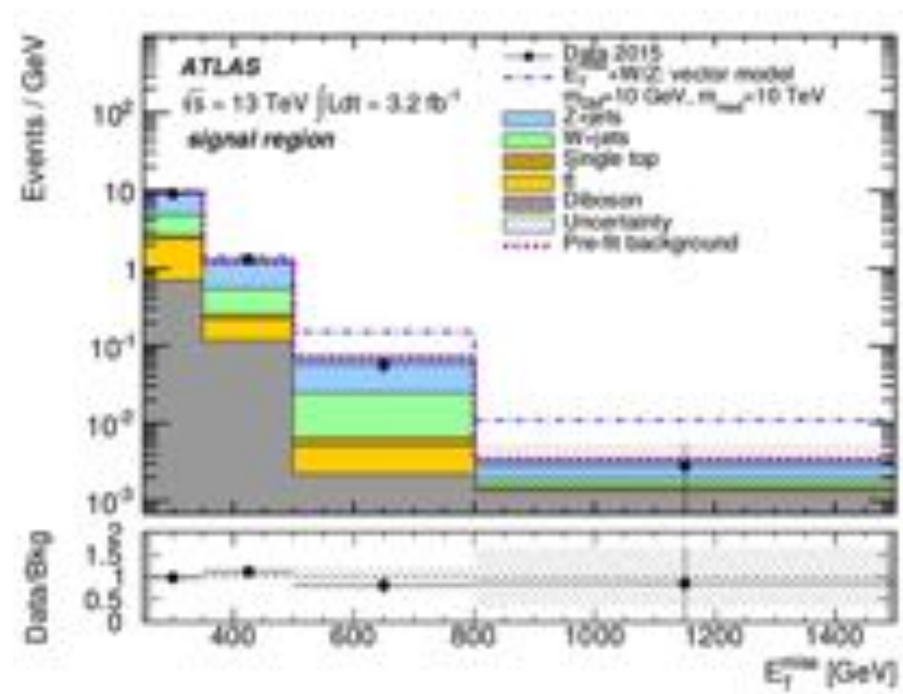
ATLAS Mono-W/Z (hadronic) Analysis

Selection: At least one large-radius jet plus large E_T^{miss}

- ➔ Hadronic decay of Lorentz-boosted W/Z boson yields merged 'wide radius' jet
- ➔ Jet reconstructed with anti-k_T algorithm with R = 0.8
- ➔ Distinguish W/Z jets by exploiting jet mass and substructure variables

Dominant Background: W/Z + jets

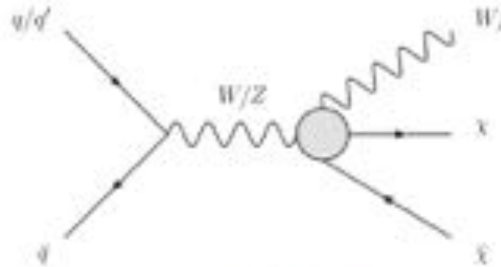


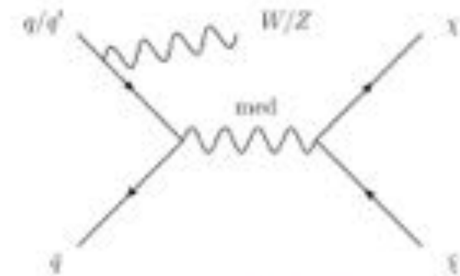


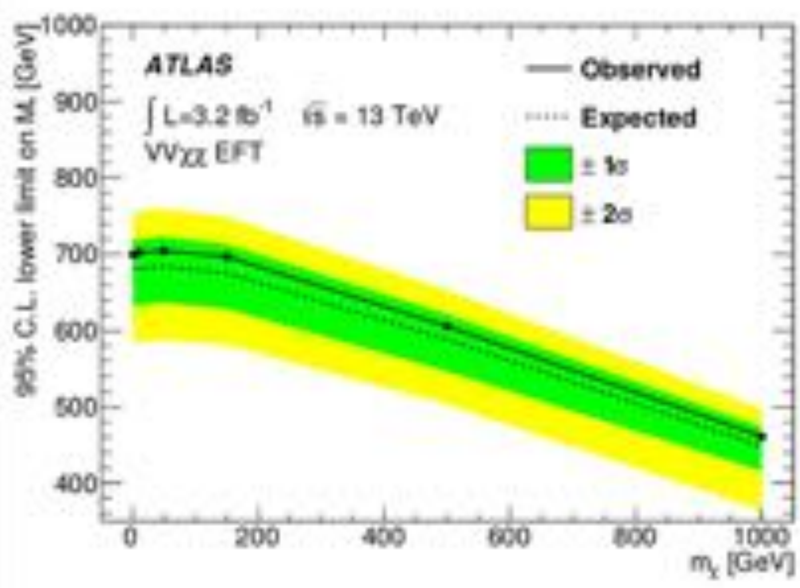
Phys. Lett. B 763 (2016) 251

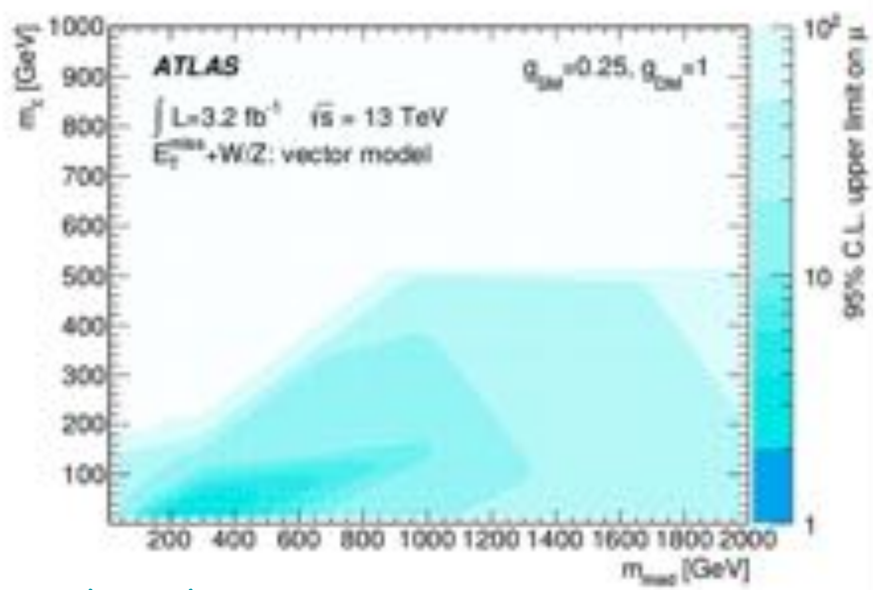
Model(s)

1. EFT $ZZ\chi\chi$ model: limit on suppression scale, M_*, with respect to m_{DM}
2. Vector-mediator simplified model: limit on signal strength, μ, in m_{DM}-M plane









[Phys. Lett. B 763 (2016) 251]

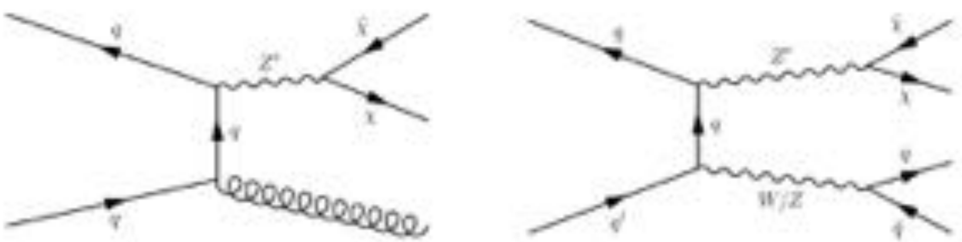
CMS Mono-Jet and Mono-W/Z (hadronic) Analysis

Selection: At least one high p_T R=0.4 jet or one R=0.8 jet from boosted W/Z boson decay plus large E_T^{miss}

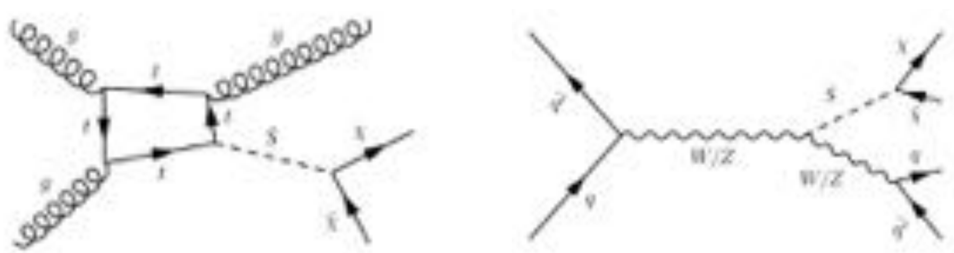
➔ Again identify W/Z jets using jet mass and substructure

Dominant backgrounds: Z(→νν) + jets, W(→lν) + jets

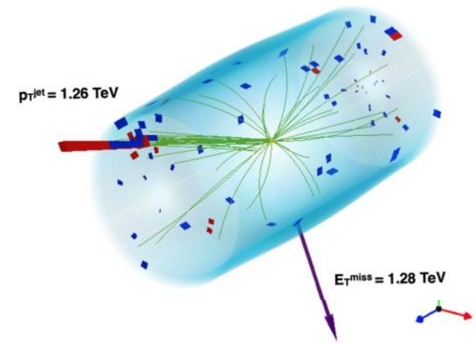
Model(s): Heavy spin-0 and spin-1 mediators coupling to quarks and Dirac fermion DM

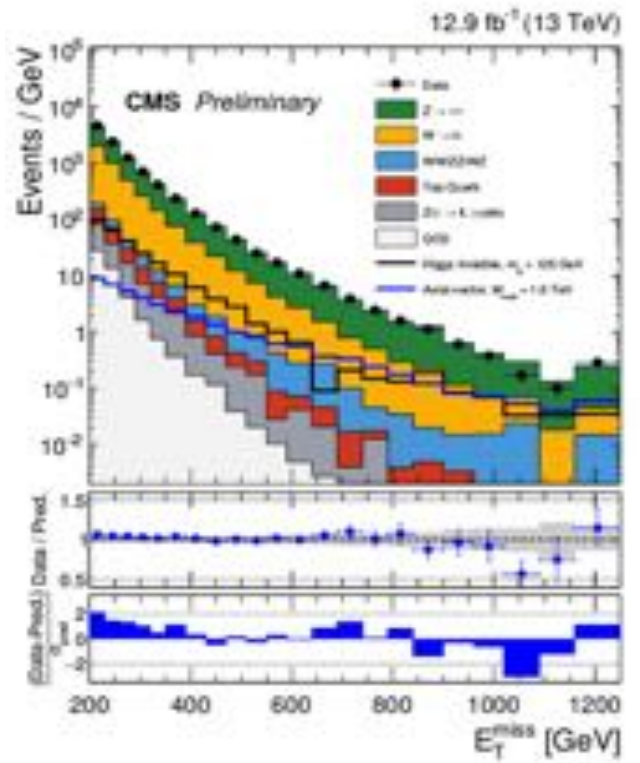


Spin-1 mediator



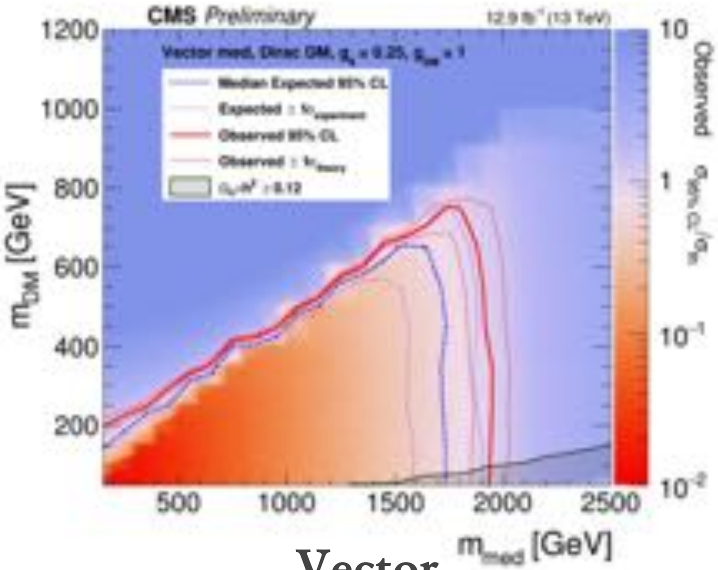
Spin-0 mediator



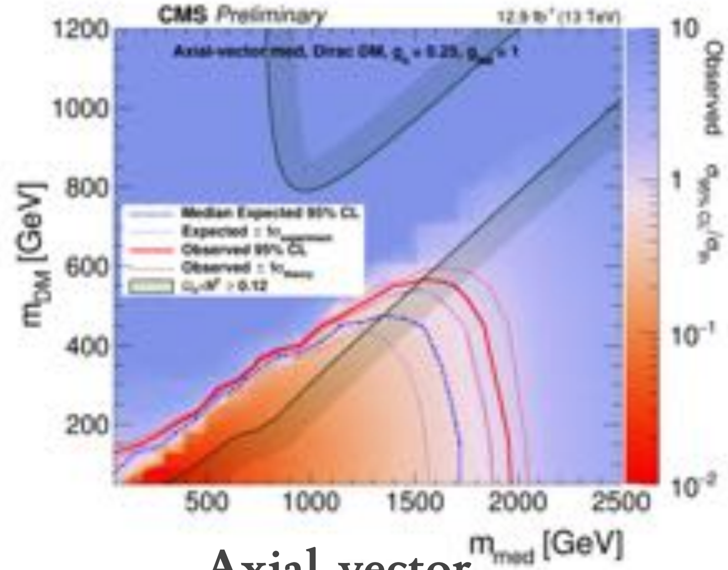


CMS PAS EXO-16-037

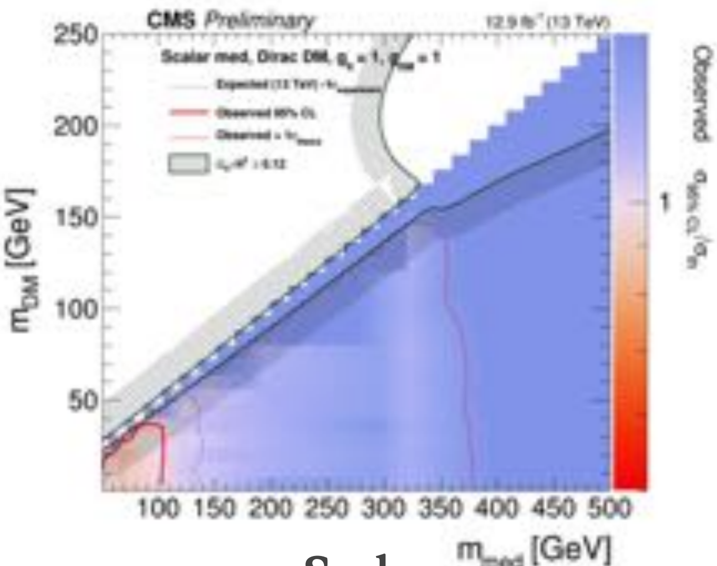
CMS Mono-Jet and Mono-W/Z (hadronic) Analysis



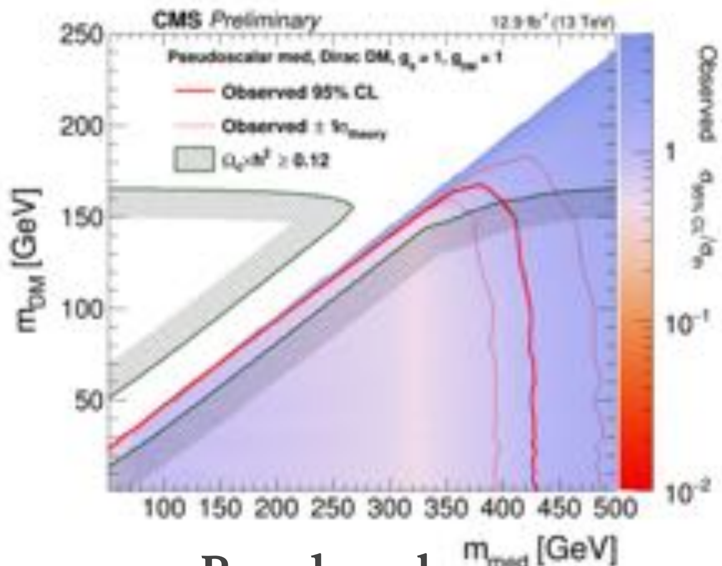
Vector



Axial-vector



Scalar



Pseudoscalar

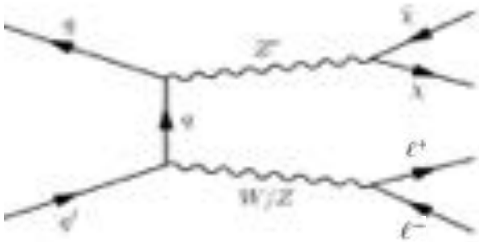
[CMS PAS EXO-16-037]

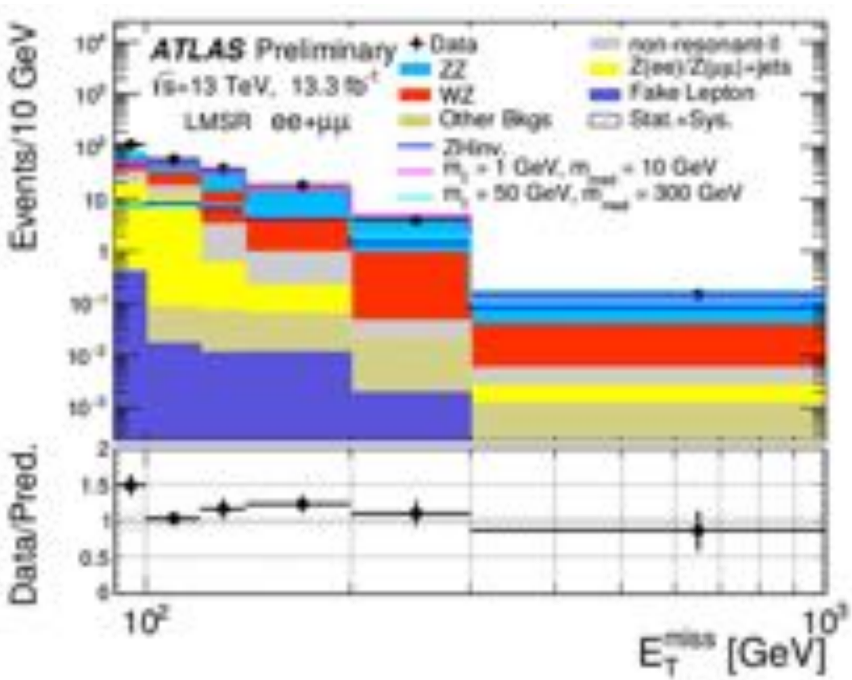
ATLAS & CMS Mono-Z (leptonic) Analyses

Selection: Two opposite-charge same-flavor leptons (e or μ) with m_T close to the Z mass, plus large E_T^{miss}

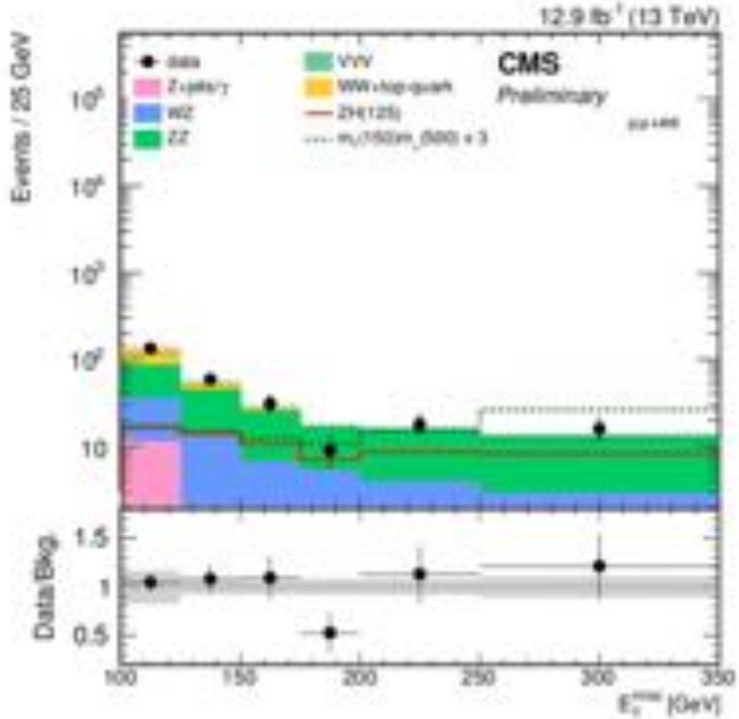
Dominant backgrounds: Z(→νν)Z(→ll) and WZ

Model(s): Heavy mediator with vector couplings.
CMS also includes a SiM with axial-vector couplings



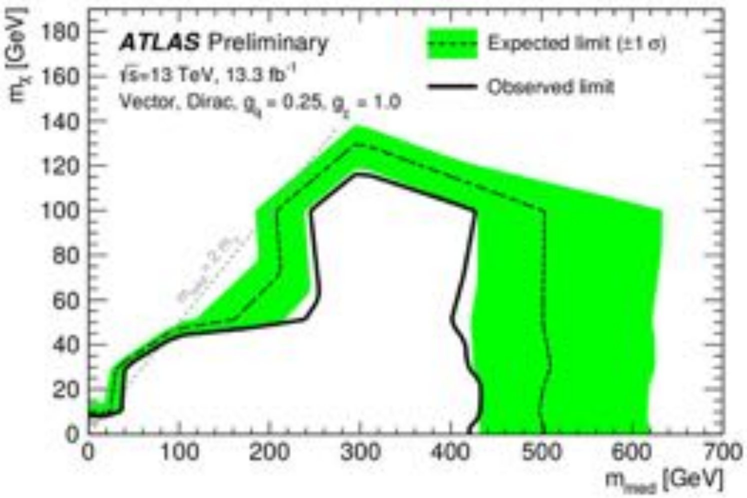


ATLAS-CONF-2016-056

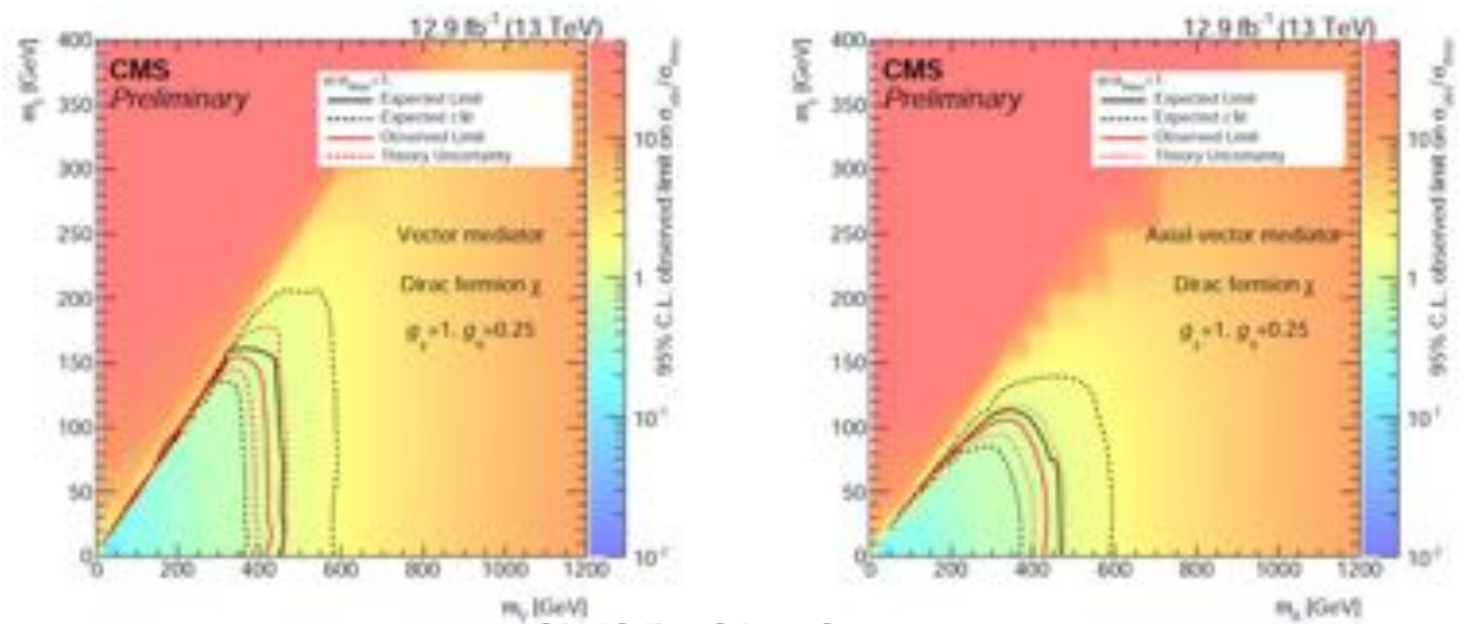


[CMS PAS EXO-16-038](CMS PAS EXO-16-038)

ATLAS & CMS Mono-Z (leptonic) Analyses



[ATLAS-CONF-2016-056]



[CMS PAS EXO-16-038]

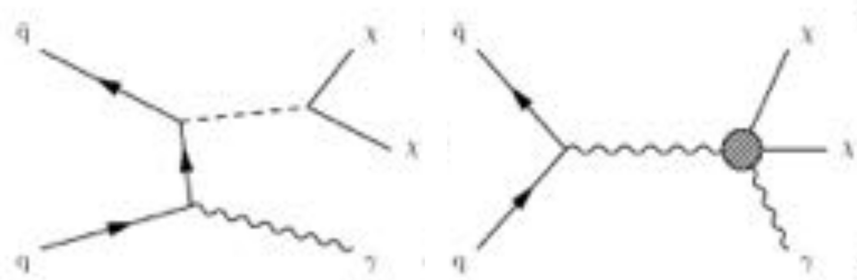
ATLAS & CMS Mono-γ Analyses

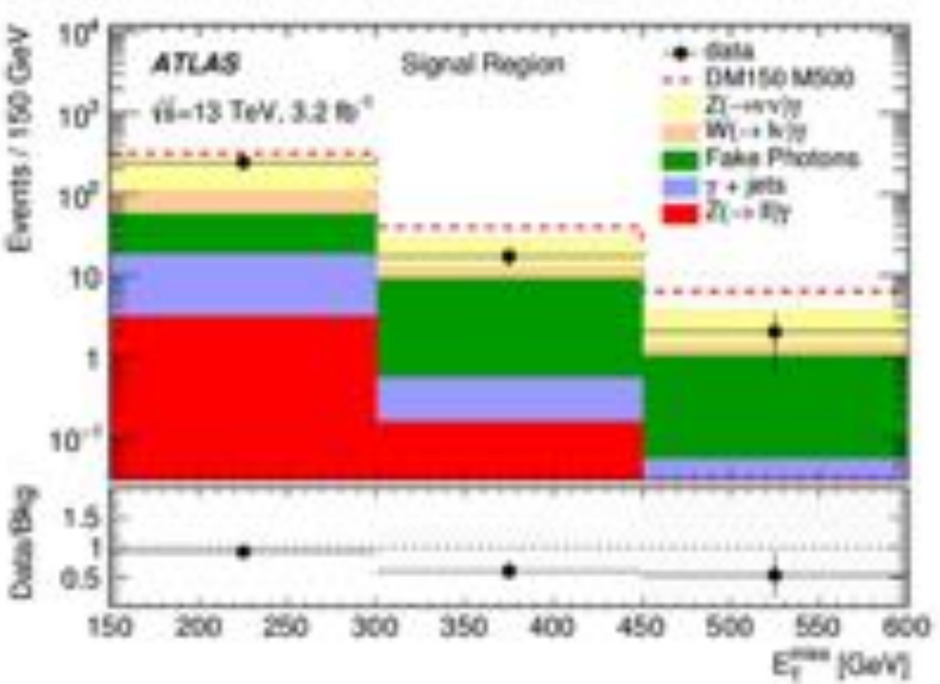
Selection: At least one high p_T isolated γ plus large E_T^{miss}

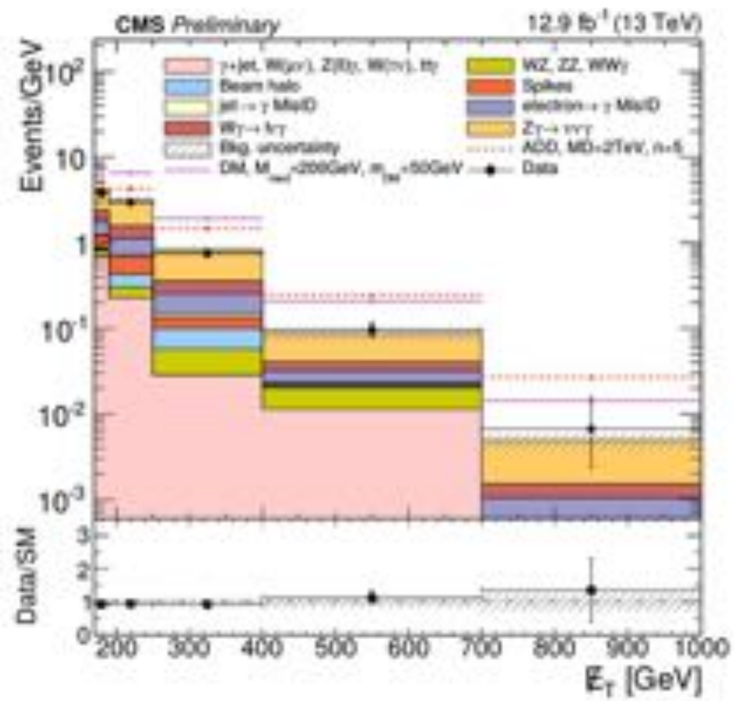
➔ Low cross-section but clean signal

Dominant background: $Z(\rightarrow \nu\nu) + \gamma$

Model(s): SiMs and an EFT γγχχ model



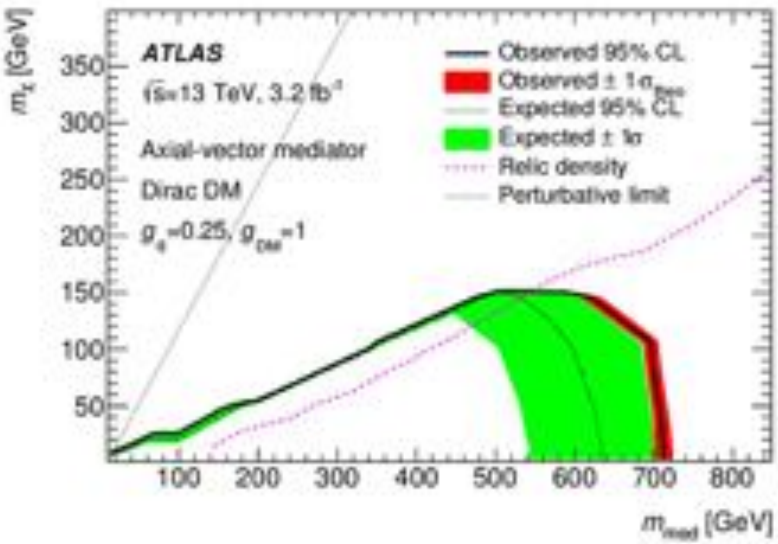


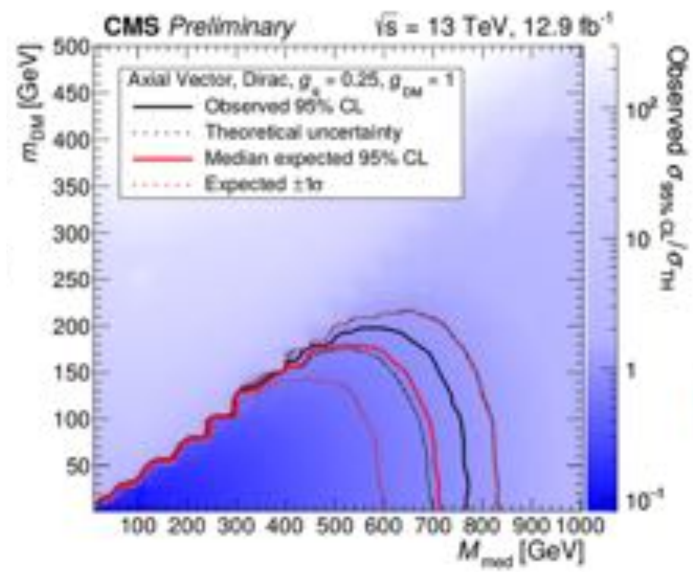


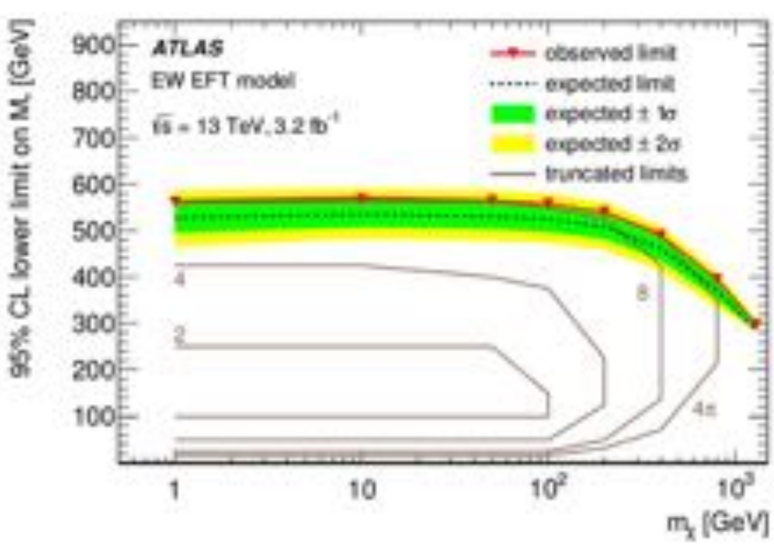
JHEP06(2016)059

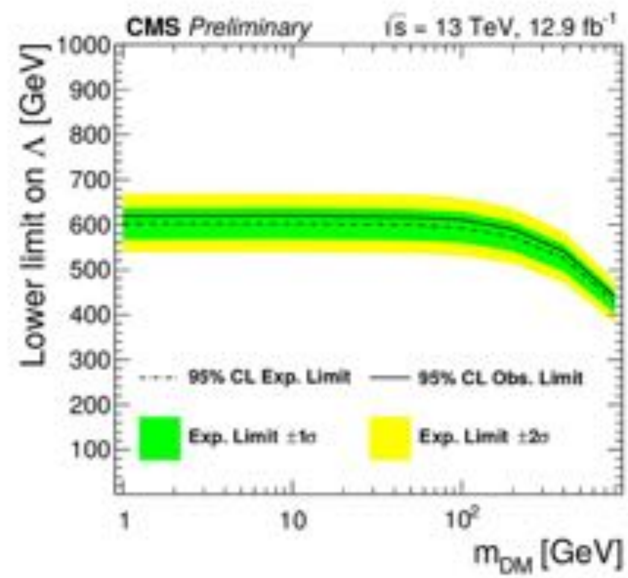
CMS PAS EXO-16-039

ATLAS & CMS Mono-γ Analyses









JHEP06(2016)059

CMS PAS EXO-16-039

ATLAS & CMS Mono-Higgs(→bb) Analyses

Higgs boson ISR highly suppressed → mono-Higgs signal provides direct probe of DM-SM coupling

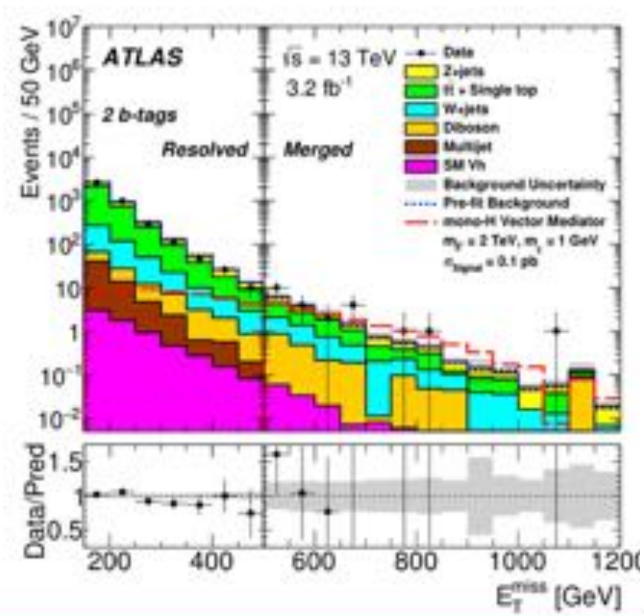
➔ h → bb dominant decay mode

Selection: resolved/merged b-jets plus large $E_{\mathrm{T}}^{\mathrm{miss}}$

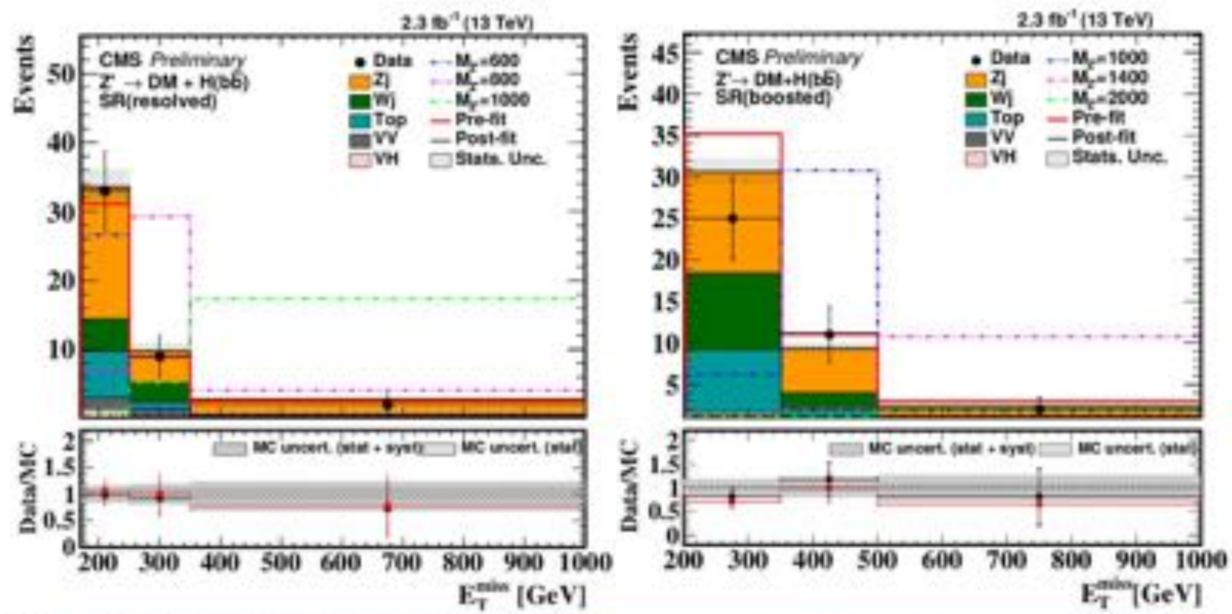
➔ Jet selection dependent on $E_{\mathrm{T}}^{\mathrm{miss}}$

Dominant background: W/Z + jets

Search for mono-Higgs(→γγ) in ATLAS-CONF-2016-087 and CMS PAS EXO-16-011, and mono-Higgs(→4l) in ATLAS-CONF-2015-059



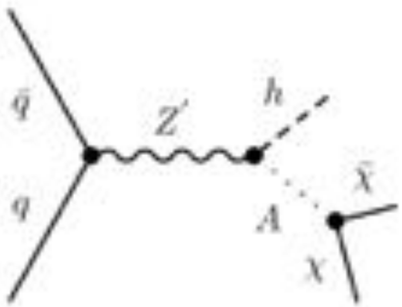
arXiv:1609.04572

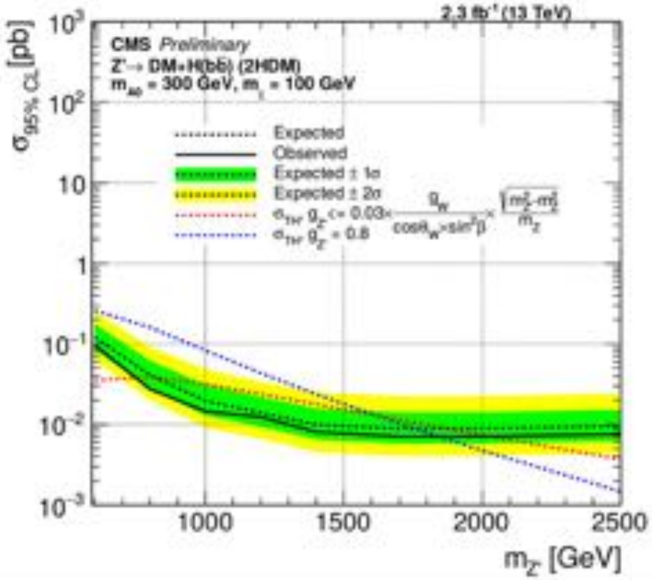


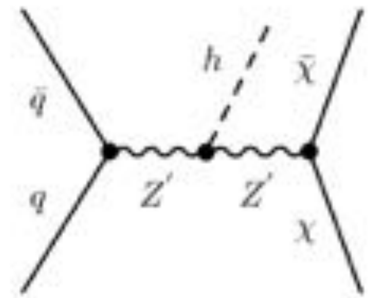
CMS PAS EXO-16-012

ATLAS & CMS Mono-Higgs(→bb) Analyses

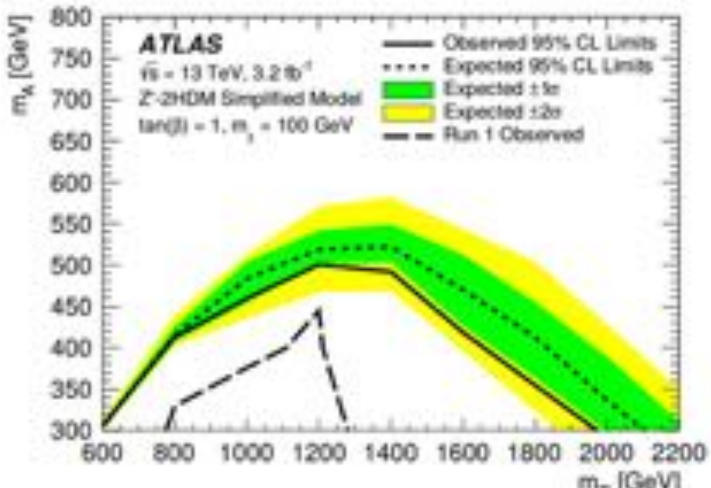
Model(s)
Z' leptophobic models

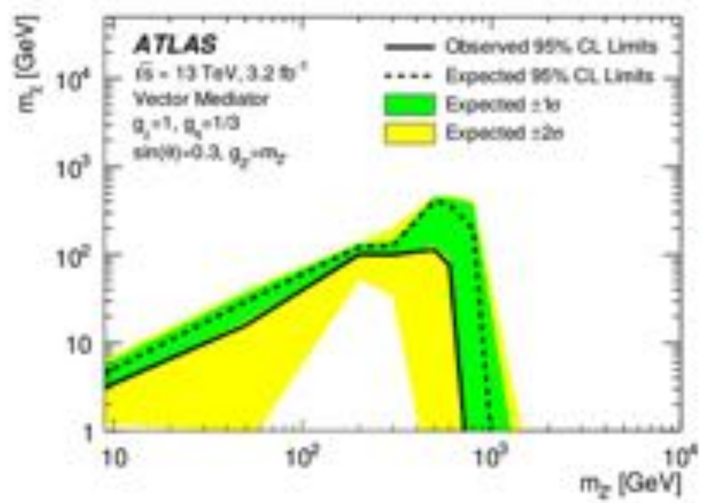






[CMS PAS EXO-16-012]





[arXiv:1609.04572]

Associate Production Searches

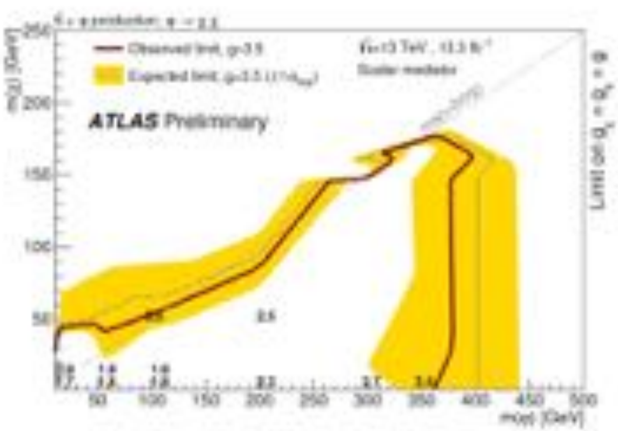
ATLAS DM Plus Top Quarks Analyses

Search for DM produced in association with top quarks
➔ Complement to mono-X analyses
➔ Most sensitive channel for spin-0 mediators

Selection: Large $E_{\mathrm{T}}^{\mathrm{miss}}$, cuts optimised for separate top quark decay modes

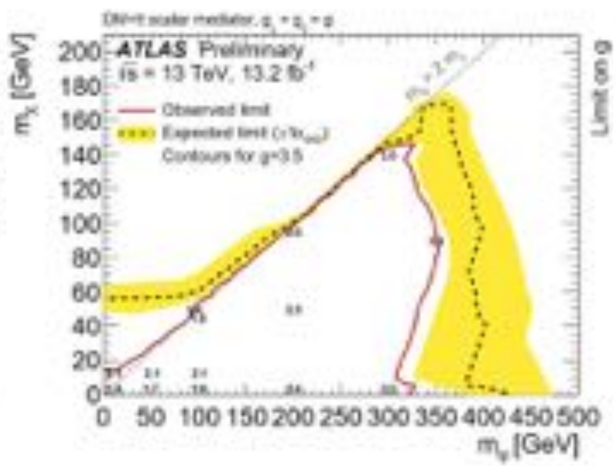
Model(s): SiMs with scalar and pseudoscalar mediators

Fully hadronic (0 leptons)



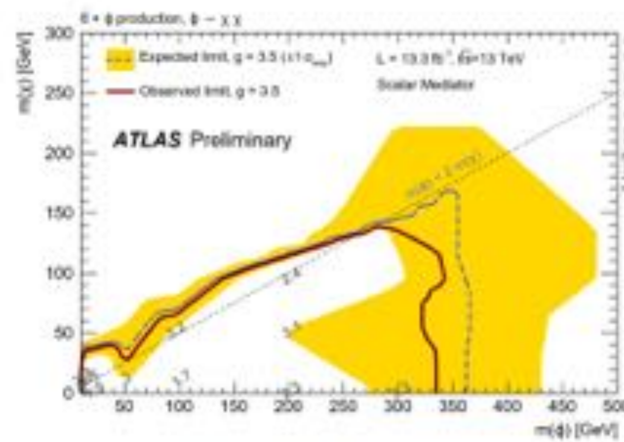
[ATLAS-CONF-2016-077]

Semi-leptonic (1 lepton + jets)



[ATLAS-CONF-2016-050]

Fully leptonic (2 leptons + jets)



[ATLAS-CONF-2016-076]

Associate production of bottom quarks also studied in [ATLAS-CONF-2016-086]

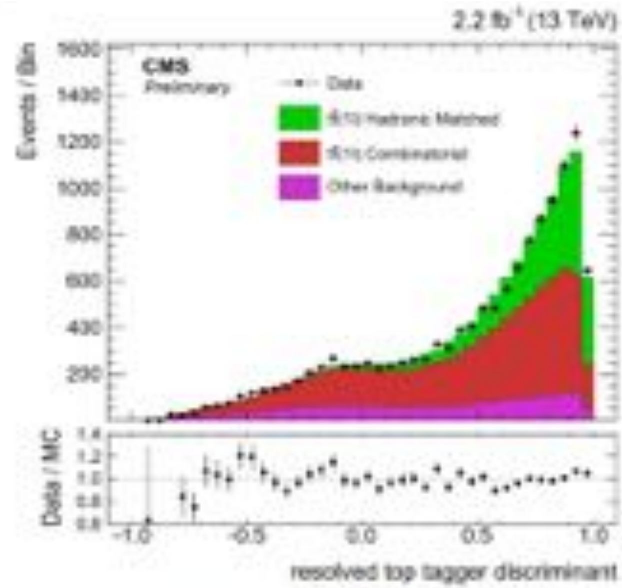
CMS DM Plus Top Quarks Analyses

Selection: Optimised for top decay mode

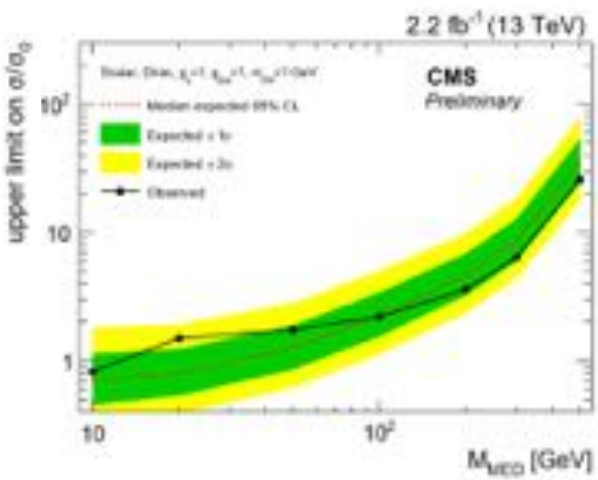
➔ Fully hadronic decays categorised by number of top-tags

Dominant Backgrounds: SM top pairs

Associate production with bottom quarks studied in CMS-PAS-B2G-15-007. Mono-top production studied in CMS PAS EXO-16-040

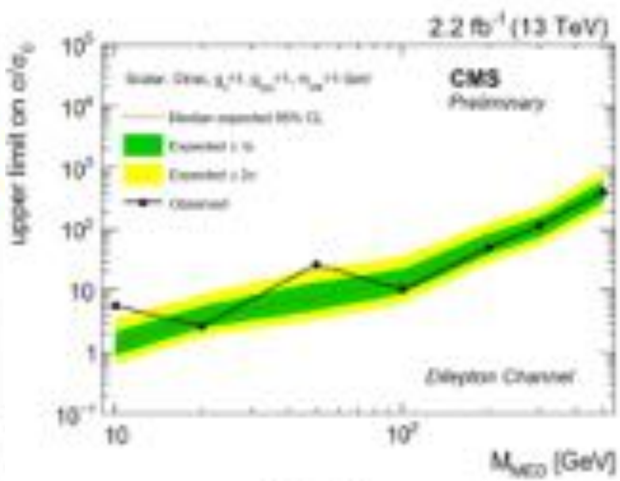


Semi-leptonic + hadronic

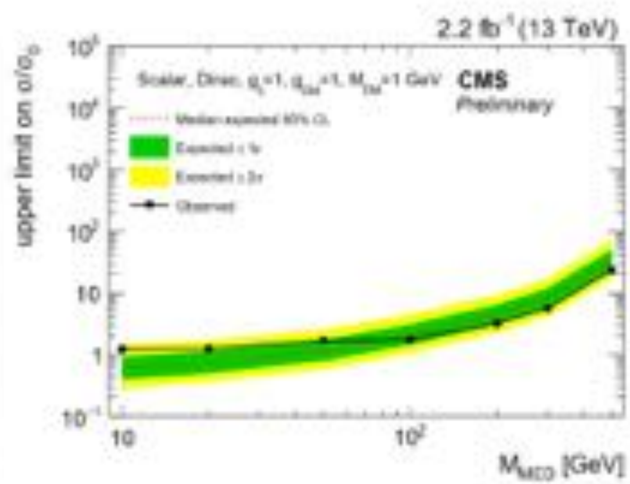


CMS-PAS-EXO-16-005

Fully leptonic



Combined



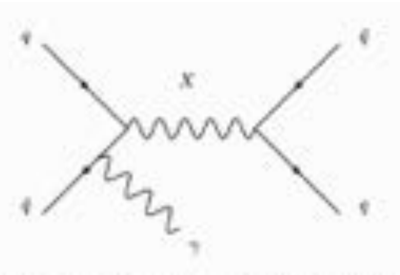
CMS-PAS-EXO-16-028

Dijet Searches

ATLAS Dijet Analyses

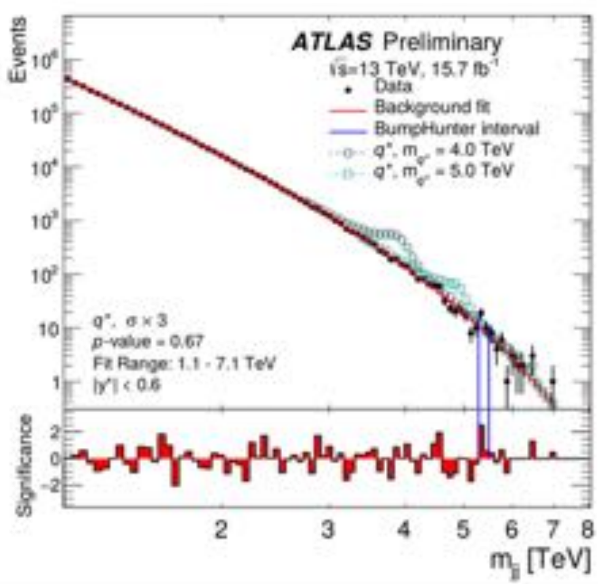
Model(s): Z' leptophobic Z' models assuming negligible branching to DM

Selection: Two jets with $|y^*| < 0.3$, $|y^*| < 0.6$ or $|y^*| < 0.8$



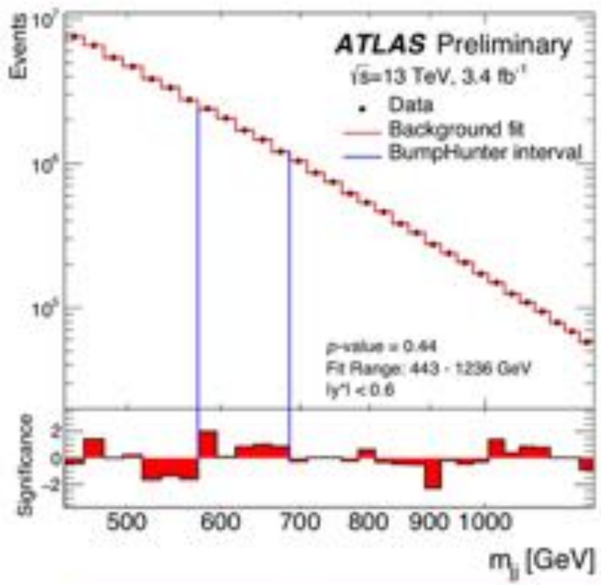
Jet p_T determines m_{jj} which can be probed
➔ different searches covering different mass ranges

Range: $m_{jj} > 1.5$ TeV



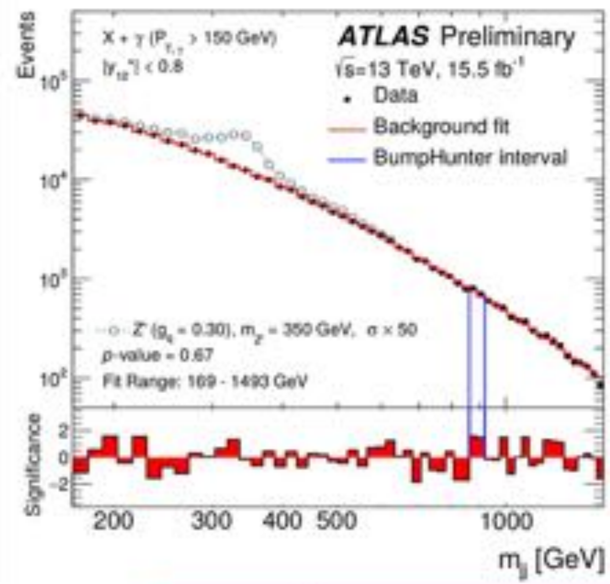
[ATLAS-CONF-2016-069]

Trigger-Level Analysis for sub-TeV masses



[ATLAS-CONF-2016-030]

Retain events with ISR γ or jet for sub-TeV masses

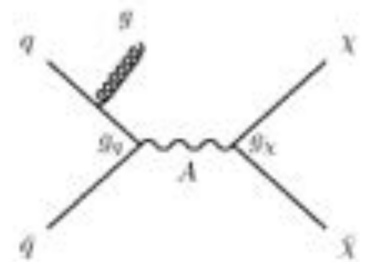


[ATLAS-CONF-2016-070]

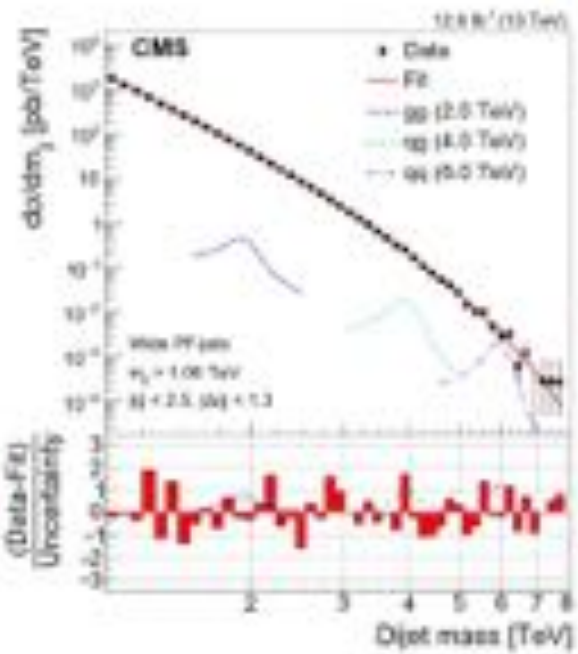
Resonance searches also conducted in di-b-jet channel in [ATLAS-CONF-2016-031]

Model(s): Z' leptophobic vector and axial-vector models

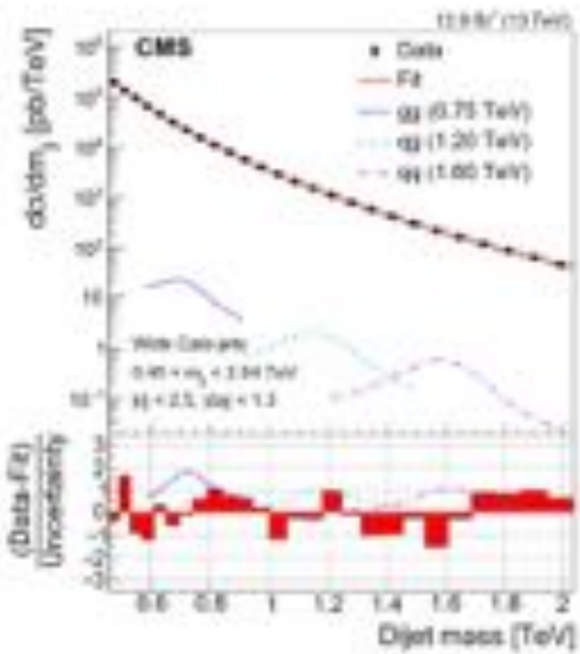
Selection: Two jets with $|\Delta\eta_{jj}| < 1.3$



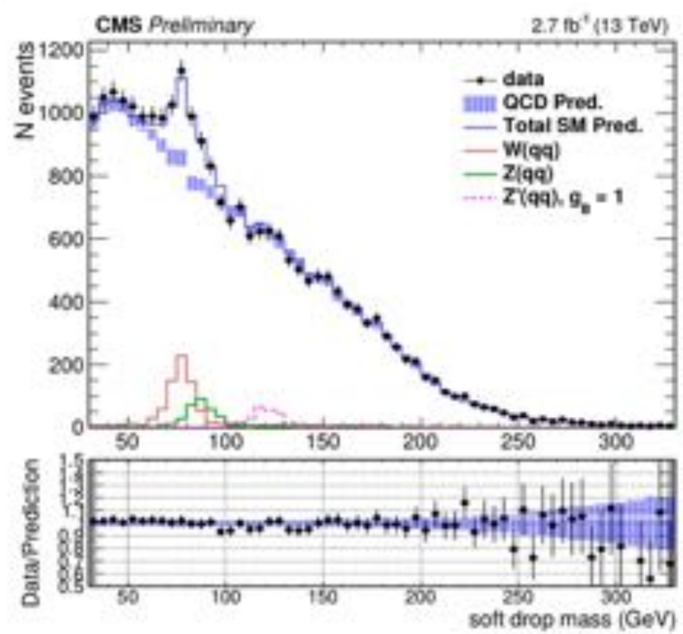
> TeV masses using PF-jets



< 2 TeV masses using trigger-level objects



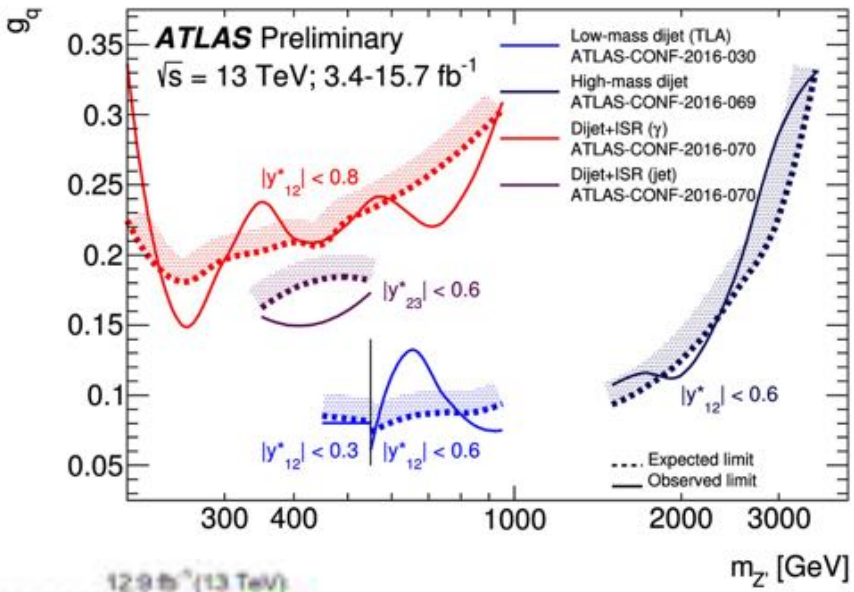
sub-TeV masses using events with ISR jet

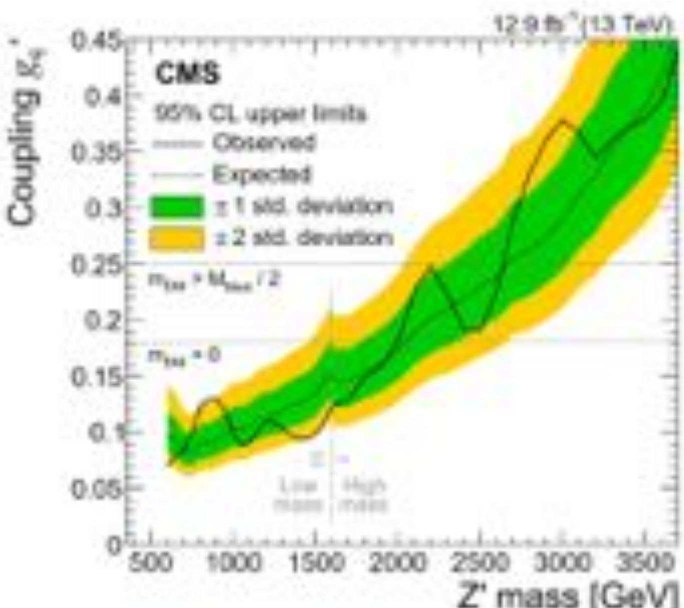


[arXiv:1611.03568](https://arxiv.org/abs/1611.03568)

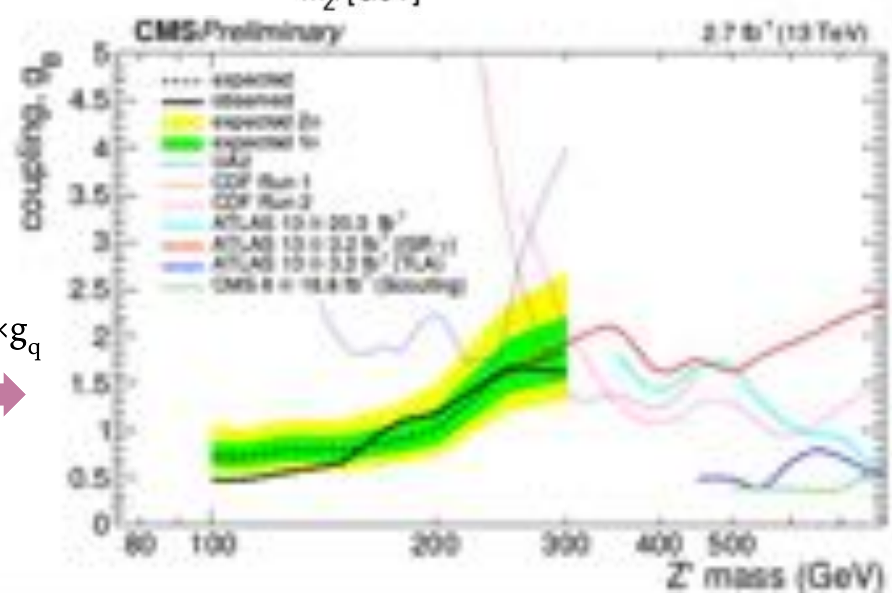
CMS PAS EXO-16-030

ATLAS & CMS Dijet Analyses





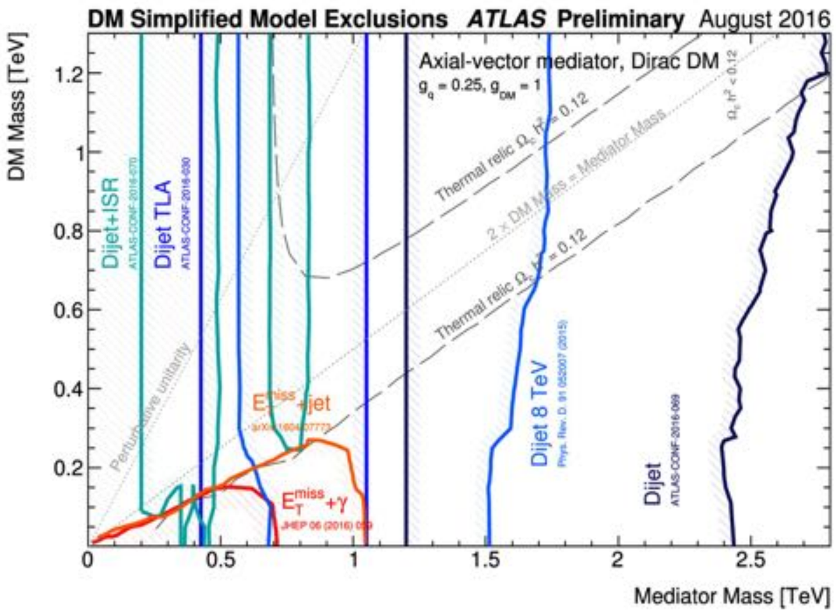
$g_B = 6 \times g_q$

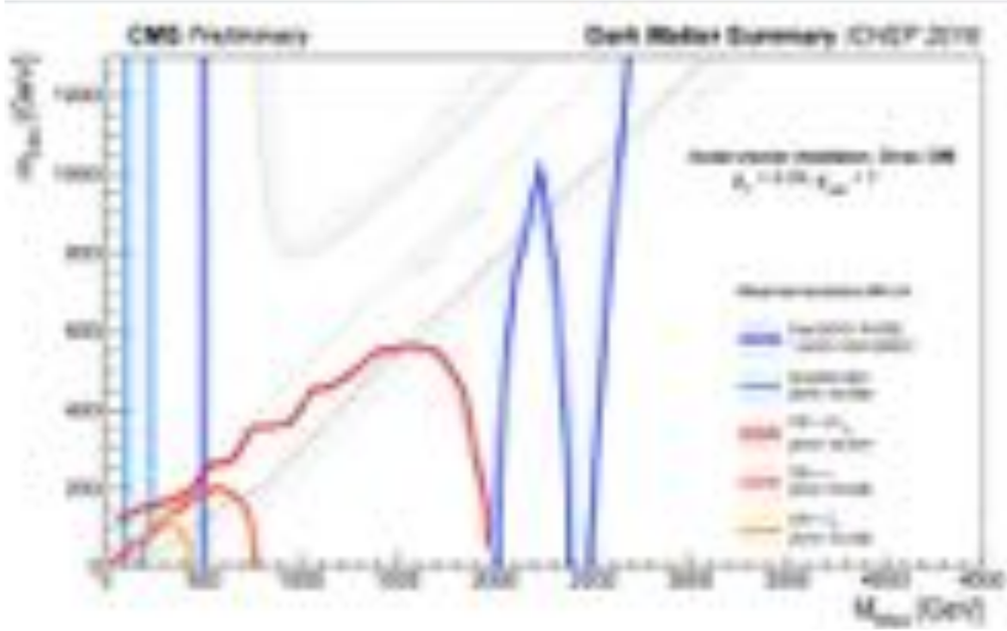


arXiv:1611.03568

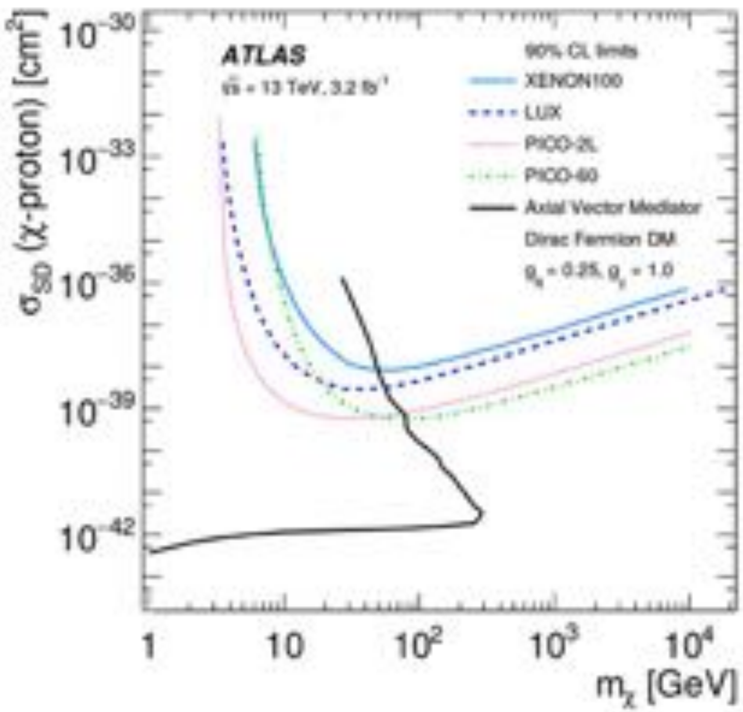
CMS PAS EXO-16-030

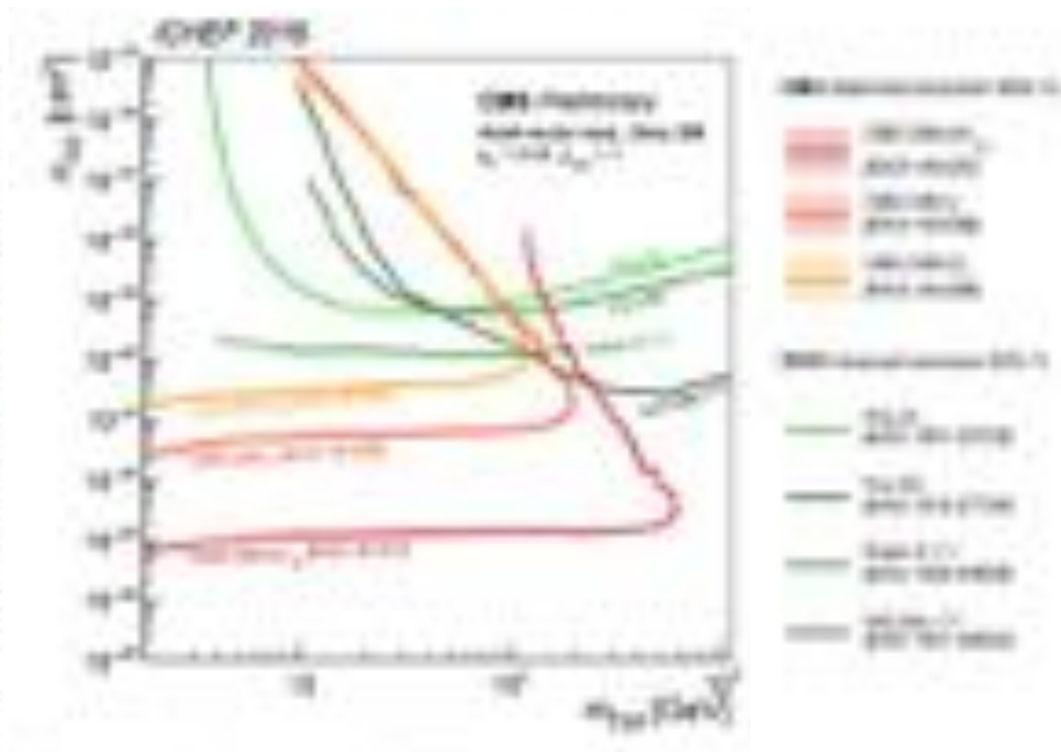
Summary of Mono-X and Dijet Search Results





Comparison with Direct & Indirect Detection Constraints





[Phys. Rev. D 94, 032005 (2016)]

Conclusions

Extensive search program for dark matter within the ATLAS and CMS experiments

➔ Complement to direct and indirect detection searches

Dark matter detection in mono-X (X = jets, W/Z/Higgs bosons, γ) plus missing transverse energy channels

Associate Production for scalar/pseudo-scalar models

Mediator detection in dijet resonance searches

No excess over SM predictions

➔ Exclusion limits interpreted within the context of a benchmark set of Simplified Dark Matter Models and Effective Field Theories

Doubling of 2016 dataset since publication of most analyses

➔ New results soon to follow!

Backup

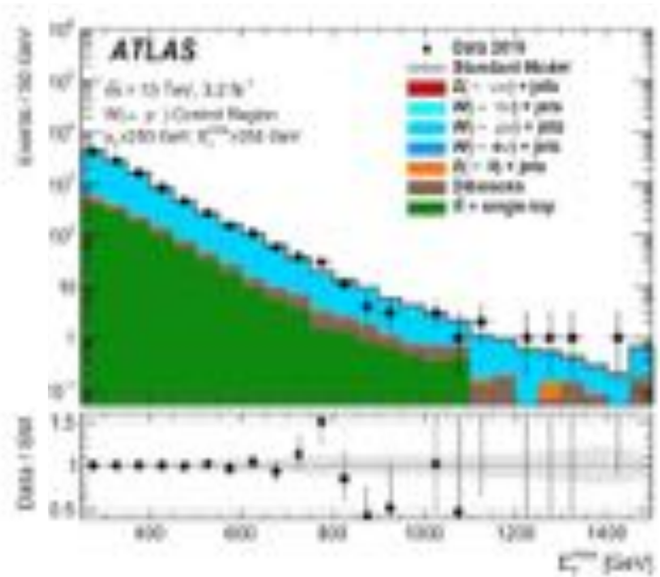
The W/Z + jets , and Z/γ*(⟶ll) + jets (l = μ, τ) backgrounds are constrained using MC samples normalized with data in dedicated control regions (CRs)

➔ Significantly reduces MC-based theoretical/experimental systematic uncertainties

Example: Z(⟶νν) + jets

1. Define a SR-orthogonal CR by reversing veto on muon
2. MC-based scale factors to extrapolate background contribution to SR:

$$N^{Z(\to\nu\bar{\nu})}_{\text{signal}} = \left(N^{\text{data}}_{W(\to\mu\nu),\text{control}} - N^{\text{non-W}}_{W(\to\mu\nu),\text{control}}\right) \times \frac{N^{\text{MC},Z(\to\nu\bar{\nu})}_{\text{signal}}}{N^{\text{MC},W(\to\mu\nu)}_{\text{control}}}$$



where $N^{\text{MC},Z(\to\nu\bar{\nu})}_{\text{signal}}$ = background from MC in the SR

$N^{\text{data}}_{W(\to\mu\nu),\text{control}}$ = number of data events in the CR

$N^{\text{MC},W(\to\mu\nu)}_{\text{control}}$ = number of W(⟶ μν) + jets in MC

$N^{\text{non-W}}_{W(\to\mu\nu),\text{control}}$ = non-W(⟶ μν) contribution (mainly due to top-quark and diboson processes)

3. Normalization factors extracted simultaneously with a global fit to all CRs which includes systematic uncertainties (and correlations)

Remaining SM backgrounds (tt, single top, and dibosons) determined using MC, non-collision/multijet contributions extracted from data

ATLAS Mono-Jet Analysis Systematic Uncertainties

Source of Uncertainty	Total Background Uncertainty
Absolute jet and MET energy scales and resolutions	±0.5% for IM1 and ±1.6% for IM7
Jet quality requirements, pileup description and corrections to the jet pT and MET	±0.2% to ±0.9%
Lepton identification and reconstruction efficiencies, energy/momentum scale and resolution	±0.1% - ±1.4% for IM1 and ±0.1% - ±2.6% for IM7
W/Z + jets renormalization/factorization, and parton-shower matching scales and PDFs	±1.1% to ±1.3%
Model uncertainties and NLO electroweak corrections for W/Z + jets	±2.0% and ±3.0% for IM1 and IM5, ±3.9% for IM7
MC-based estimate of tt and single-top cross-sections	±2.7% and ±3.3% for IM1 and IM7
MC-based estimate of diboson contribution	±0.05% and ±0.4%
±100% uncertainty on multijet and NC backgrounds	±0.2% for IM1
Statistical limitations (CRs and MC samples)	±2.5% for IM1 and ±10% for IM7

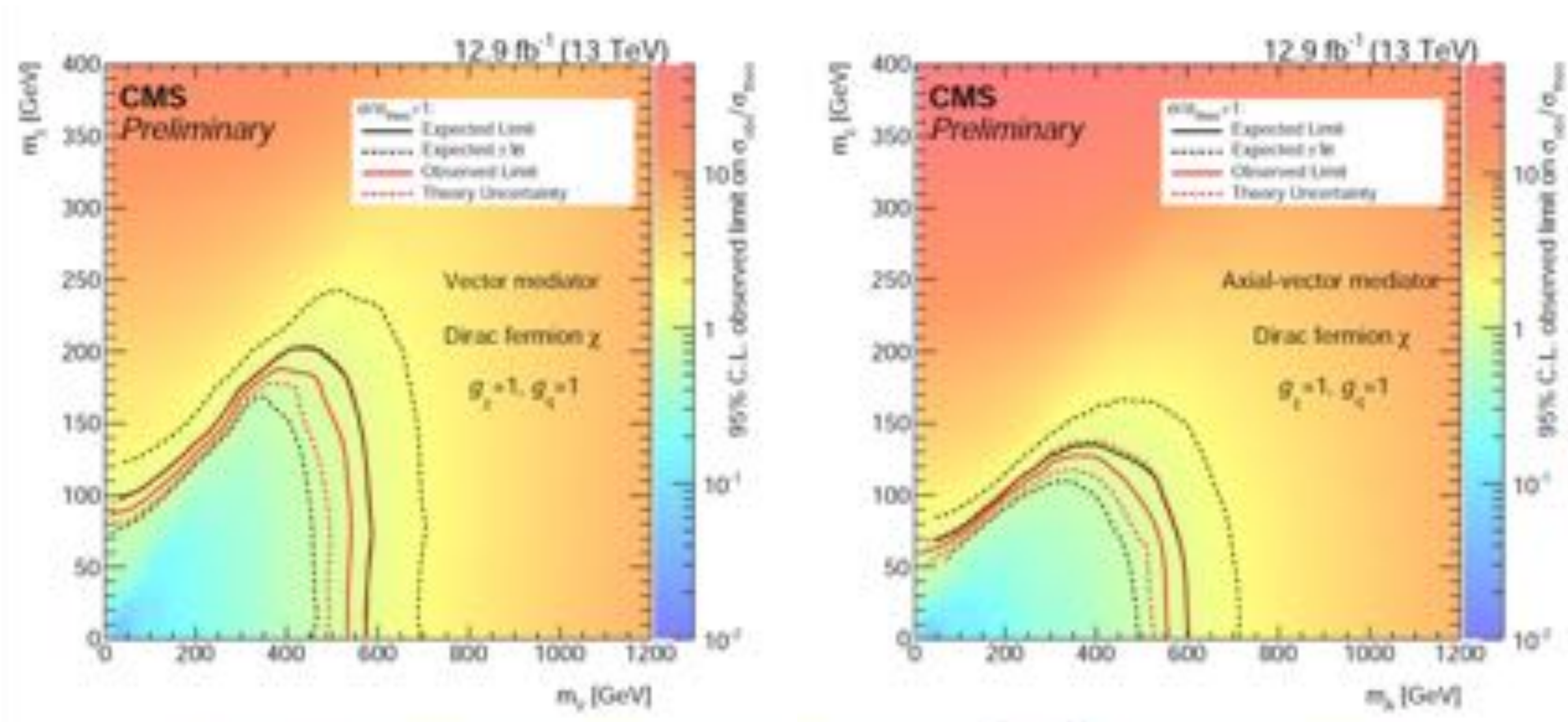
- All systematic uncertainties treated as nuisance parameters with Gaussian shapes in fit to MET bins

CMS Mono-Z (leptonic) Analysis Systematic Uncertainties

Source of uncertainty	Bkg. unc. (%)	Simplified Model unc. Exp. (%)	Simplified Model unc. Theory (%)	Impact
Integrated luminosity	6.2	6.2	—	9.5
Lepton trigger & identification efficiency	4	4	—	
Lepton momentum scale and resolution	2	2	—	
Jet energy scale, resolution	0.5	0.4	—	7.7
b-tagging efficiency	2	2	—	
Pileup	0.6	0.6	—	
Efficiency for missed lepton (WZ)	2.2	—	—	
PDFs, α_s	1.4	—	1.8	0.9
Renorm./fact. scales (signal)	—	—	5.8	
Renorm./fact. scales (VV)	2.5	—	—	5.4
Renorm./fact. scales (VVV)	5.5	—	—	
Renorm./fact. scales ($gg \to ZZ$)	1.0	—	—	
Electroweak corrections on $q\bar{q} \to VV$	7.6	—	—	5.5
Underlying event	—	—	3	2.9
DY normalization	100	—	—	1.4
$t\bar{t}$, tW, W^+W^-, W+jets normalization	14.0	—	—	1.2
MC statistics (signal)	—	1.1	—	
MC statistics (ZZ, WZ, VVV)	1.4	—	—	2.4
MC statistics (DY)	43	—	—	
MC statistics ($t\bar{t}$, tW, W^+W^-)	10.5	—	—	

Impact: relative change of the expected best fit signal strength that is introduced by the variation for a simplified model signal scenario with a vector mediator of mass 200 GeV and m_{DM} = 50 GeV

CMS Mono-Z (leptonic) Analysis



[CMS PAS EXO-16-038](CMS PAS EXO-16-038)

ATLAS & CMS Mono-Higgs(→γγ) Analyses

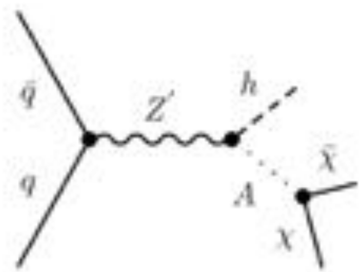
$h \rightarrow \gamma\gamma$ has low BR but clean signal

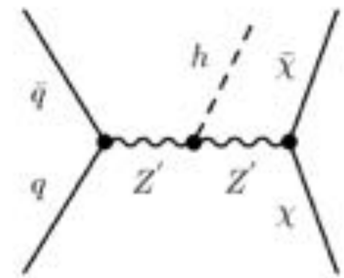
➔ look for **excess in** the $m_{\gamma\gamma}$ spectrum

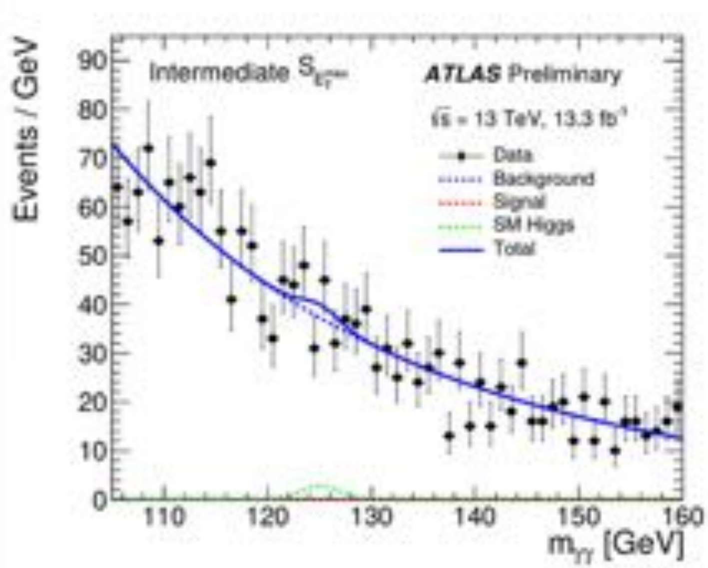
Selection: Two high p_T isolated photons plus large E_T^{miss}

Dominant backgrounds: Resonant and non-resonant contributions

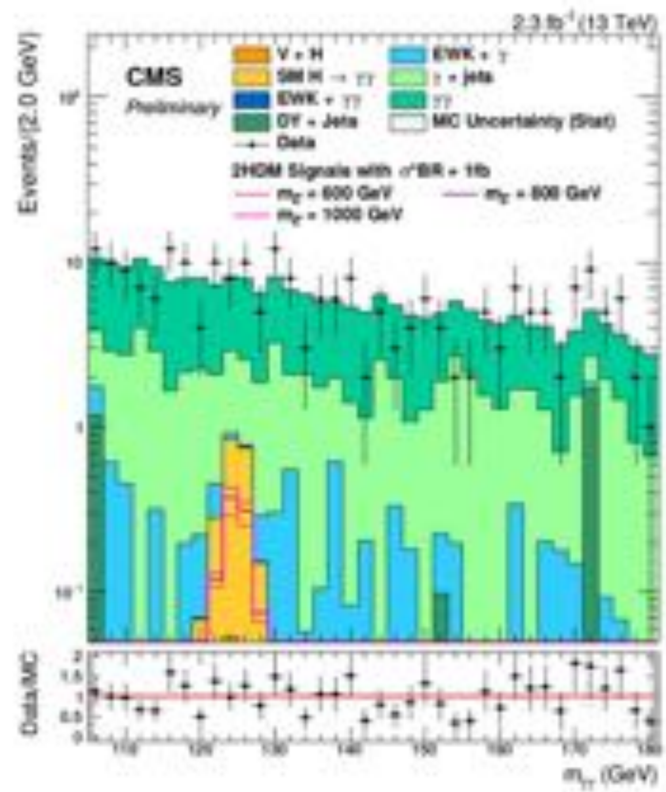
Model(s): Z' leptophobic models





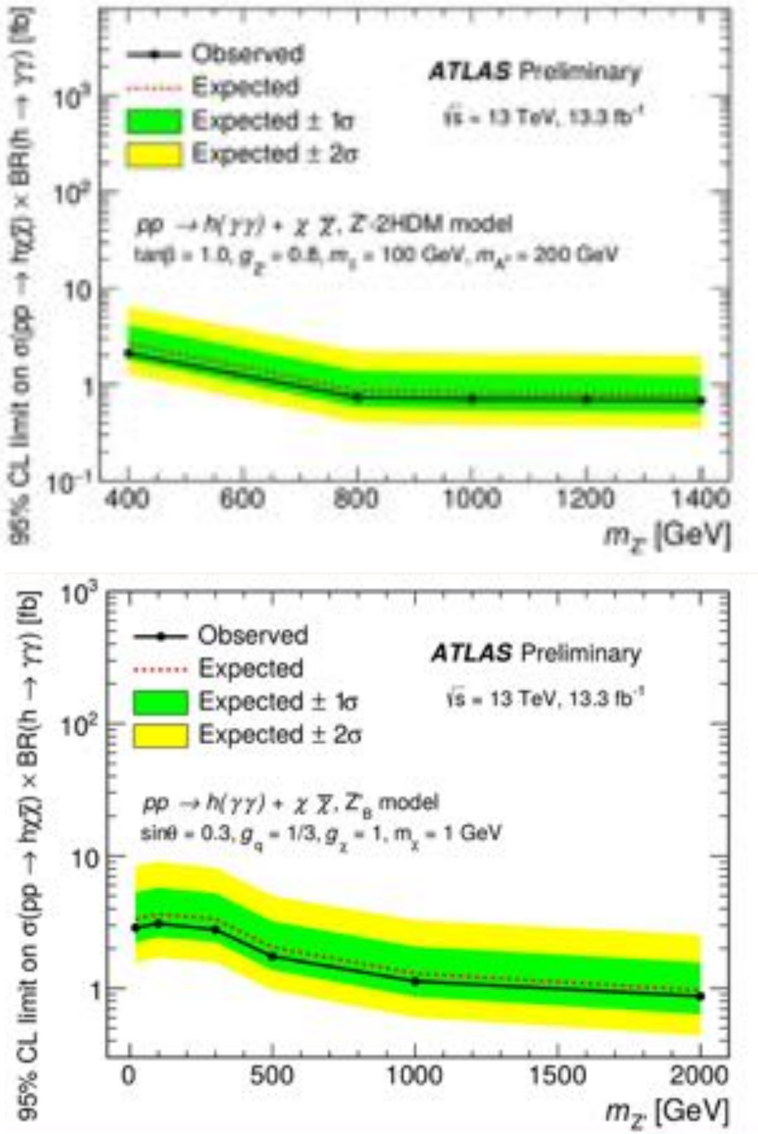


[ATLAS-CONF-2016-087]

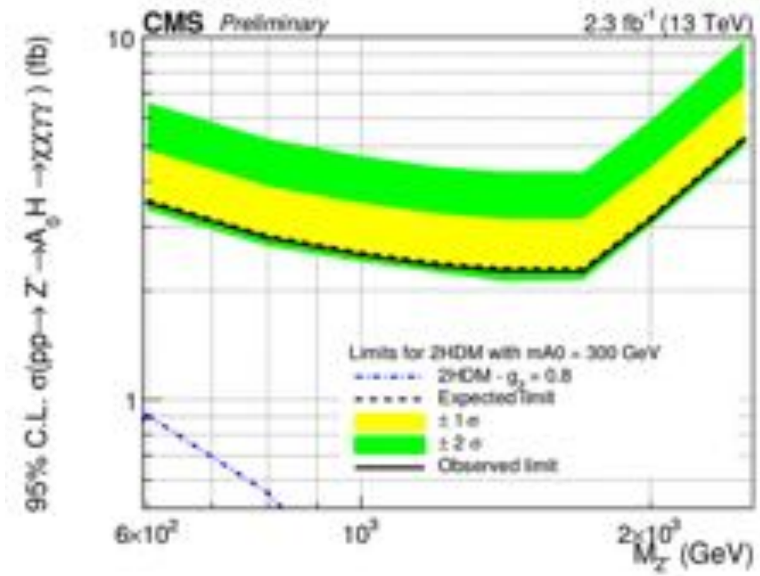


[CMS PAS EXO-16-011]

ATLAS & CMS Mono-Higgs(→γγ) Analyses



ATLAS-CONF-2016-087

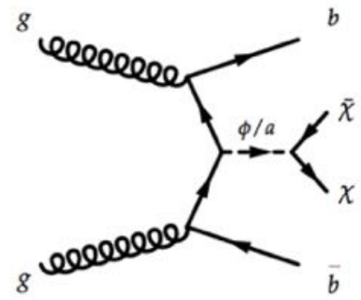


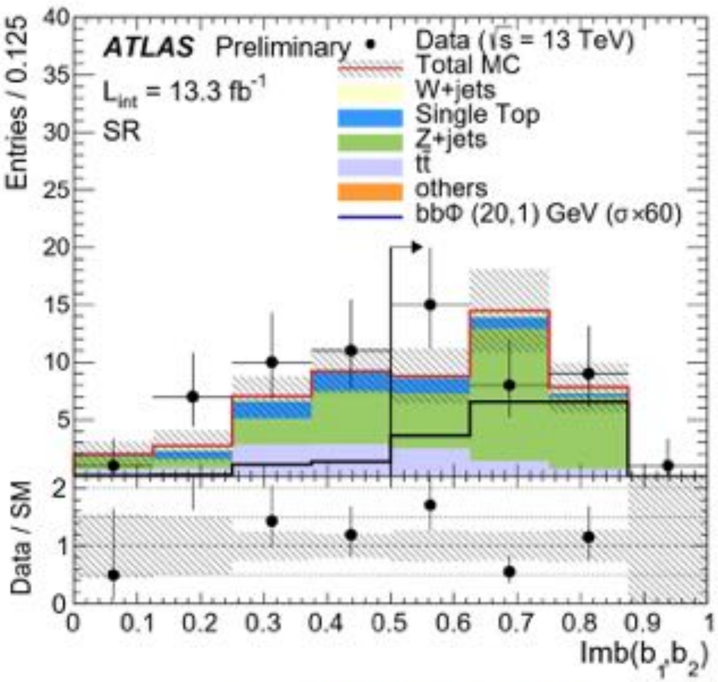
CMS PAS EXO-16-011

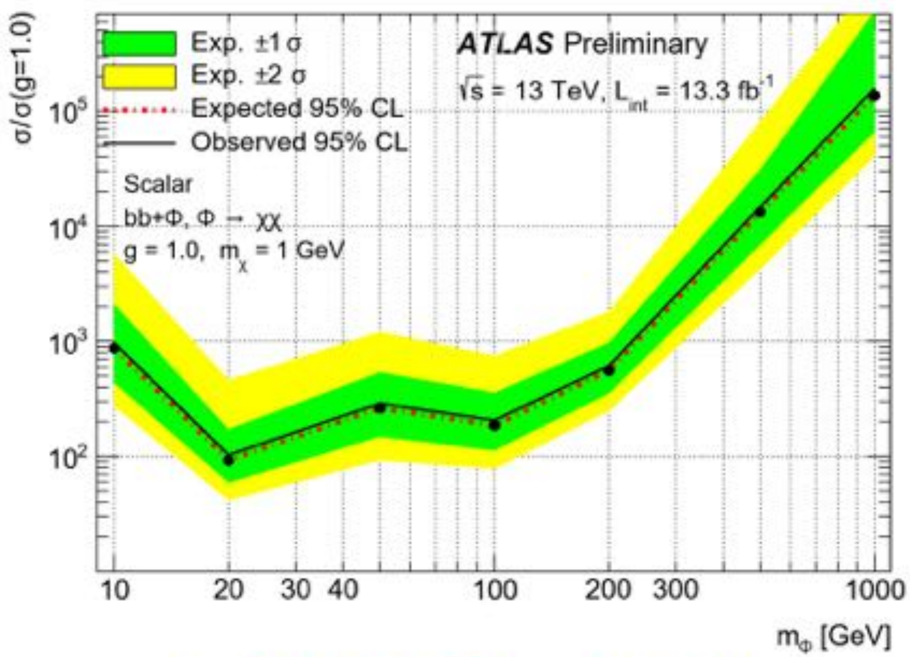
Search for DM produced in association with bottom quarks

Selection: Two b-tagged jets plus large $E_{\mathrm{T}}^{\mathrm{miss}}$

Model(s): Scalar and pseudoscalar mediators with Dirac fermion DM







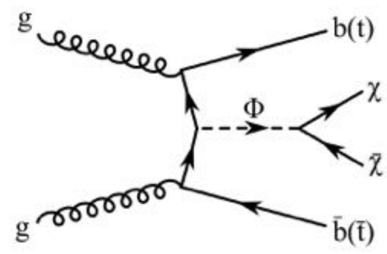
ATLAS-CONF-2016-086

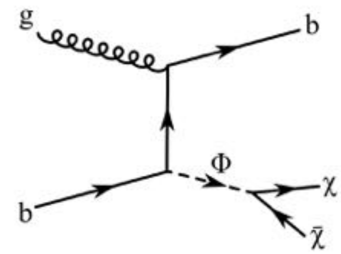
CMS DM Plus Bottom Quarks Analysis

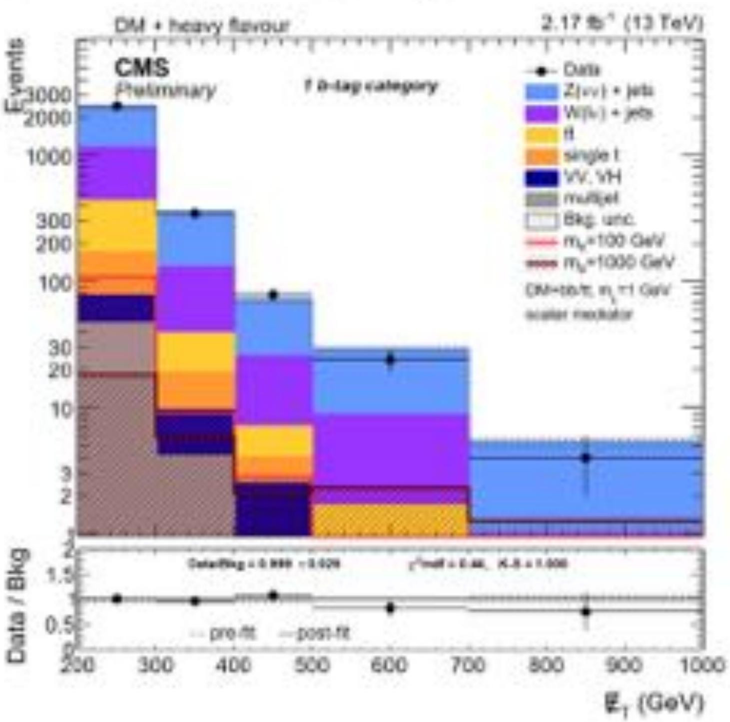
$E_{\mathrm{T}}^{\mathrm{miss}}$+ bb searches also sensitive to $E_{\mathrm{T}}^{\mathrm{miss}}$ + tt production

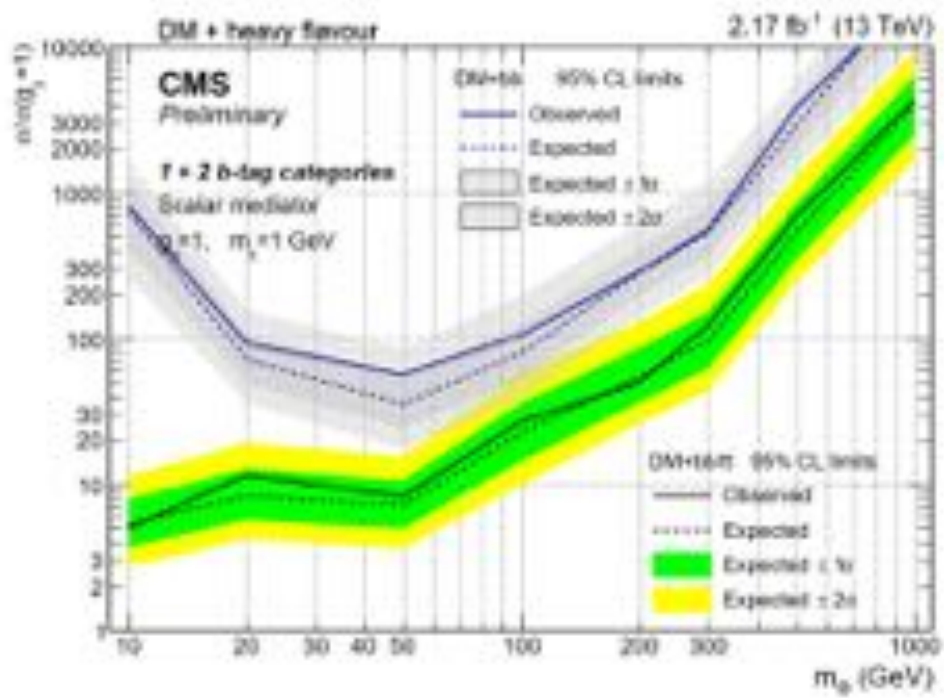
➔ b quarks produced in top quark decays

Selection: Two signal regions categorised by either one or two b-tagged jets plus large $E_{\mathrm{T}}^{\mathrm{miss}}$









CMS PAS B2G-15-007

Trigger-Object Level Analysis

Bandwidth allocation for single-jet triggers limits statistics for particles lighter than 1 TeV

➔ Full event information requires trigger prescale (1/prescale factor events recorded)

To avoid prescaling, threshold p_T of the jet must be large → restricts minimum m_{jj}

For lighter masses, instead record partially-built event information

1. L1 identifies ROI in 0.2 x 0.2 calorimeter segments
2. HLT reconstructs and calibrates 'trigger' jet
3. ROI with E_T > 75 GeV at EM scale → record summary of trigger jet to **Trigger-Object Level Analysis (TLA)** stream, including 4-momentum and jet ID variables, excluding readout from tracking and muon detectors

Partially-built events are <5% of full event size, allowing for higher rates to be recorded (2 kHz)

Offline trigger jets calibration akin to fully-reconstructed jets

➔ μ correction

➔ Trigger jet specific MC-based JES calibration

➔ No GSC correction (missing ID and muon spectrometer information)

➔ Dedicated correction for trigger jets